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ROOF RESPONSE TO ICING CONDITIONS,(U)
JUL 79 J W LANE, S J MARSHALL, R H MUNIS
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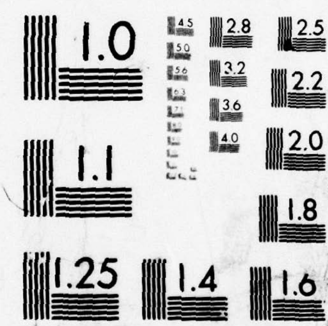

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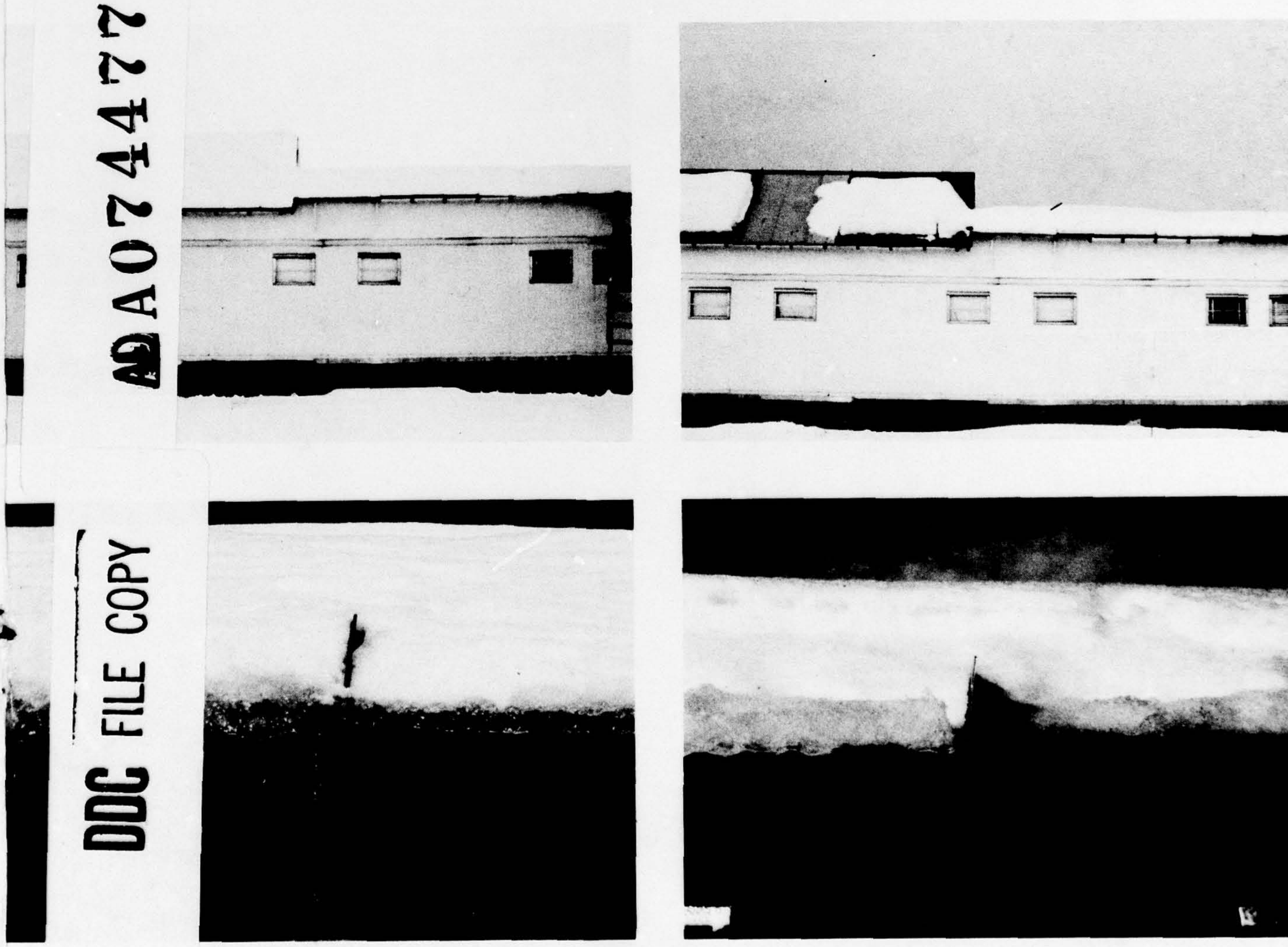

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Cover: Photos of the six test roofs showing that aluminum roofs of the higher slope tend to shed their snow cover almost immediately, while those of the lower slope tend to develop ice dams at the eaves that prevent the loss of snow cover and create numerous problems. The asphalt and cedar shingle roofs behave more similarly at the two different slopes.

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J.W. Lane, S.J. Marshall ~~and~~ R.H. Munis

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Six test roofs of two different slopes – 16.3° and 39.8°, and three different roof coverings – asphalt shingles, cedar shingles, and corrugated aluminum sheeting, were constructed at USACRREL, Hanover, New Hampshire, and were instrumented with thermocouples, heat flow meters, and calibrated gutters. Measurements were recorded for the winters of 1971-72 and 1972-73. The degree of icing and the chronological changes in the snow cover were recorded on 35-mm Kodachrome slides. It was found that eave icing is a sensitive function of the slope, roof covering composition, and solar radiation. The effects of wind were not investigated; the data were screened to remove all information corresponding to windspeeds over 8 km/h. In order of increasing tendency to form ice dams on the eaves, the

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roofs were high-slope asphalt, high-slope cedar, high-slope aluminum, low-slope asphalt, low-slope cedar, and low-slope aluminum.

PREFACE

This report was prepared by Captain Jean W. Lane, R&D Coordinator, Stephen J. Marshall, Physical Science Technician, and Dr. Richard H. Munis, Research Physicist, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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This report was technically reviewed by Dr. Haldor Aamot and Kevin L. Carey of CRREL.

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CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

The response of a roof to its snow cover and the environment is a complex phenomenon depending sensitively on the design and construction of the roof. This study investigated the roles of the slope and composition of the roof covering.

When there is no snow cover before snow begins to fall, the slope of the roof dominates its icing behavior by controlling the interaction with solar radiation and attic heat, the rate of fall of snow sliding from the roof, and the rate of flow of meltwater from the roof. In general, as the slope increases, the attic air, and the middle section, eaves, and lower section of the roof increase in temperature while the temperature of the ridge decreases.

Interfering with the action of the slope on a roof's snow cover are the smoothness of the roof covering and its thermal characteristics. Shingles with large butt ends impede the fall of snow from the roof. If its solar absorptivity is low, the roof's surface does not interact strongly with solar radiation even though optimally exposed by a high slope. If the roof's thermal conductivity and diffusivity are low, it may be able to absorb large amounts of thermal energy without a change in temperature significant enough to melt its snow cover, thereby reducing the effects of solar radiation, attic heat, and heat trapped under the eaves.

Once any ice has formed on the eaves, it acts as a barrier to the flow of meltwater and sliding snow while also acting to maintain the eaves at a cooler temperature than the middle section of the roof, producing and maintaining the temperature profile that leads to more icing. Under these circumstances, the roles of the thermal and optical characteristics of the roof dominate the icing behavior.

To reduce or eliminate icing, a roof may be designed to have a high enough slope to eliminate as much of the snow cover as possible through the action of gravity. This must not enable the roof to interact with solar radiation and attic heat enough to cause a temperature rise of the middle section sufficient to generate meltwater that may become ice at the eaves. The thermal properties of the roof covering must be chosen to compensate for higher slope. An alternative approach is to design the roof with a low slope and rough surface so that its exposure to solar heating is reduced and a sufficiently deep snow cover is retained to insulate its surface from the exposure to solar radiation that cannot be avoided. In the latter case, it is important to insulate the attic floor and the underside of the eaves while constructing the roof of materials of low thermal conductivity.

In order to promote improvements in roof design, it would be wise to direct future research into better measurements of the thermal and optical properties of roof materials and to study the detailed interactions between snow cover, roof characteristics, and environmental variables. Efforts are currently being made in these directions.[1,6,8,11,12]

ROOF RESPONSE TO ICING CONDITIONS

J.W. Lane, S.J. Marshall and R.H. Munis

INTRODUCTION

Roofs for use in cold regions should be designed to minimize icing and enhance the thermal integrity of the total building. The former problem has long been considered important, and the recent emphasis on energy conservation has focused attention on the latter.[1 2 10] The purpose of this work is to describe the thermal response of a roof (as a function of its design) to the conditions that promote icing.

The variables with which this work will deal can be divided into three different types: 1) variables that specify the design of the roof, "roof characteristics"; 2) variables that specify the thermal response of the roof, "roof responses"; and 3) variables that specify the icing conditions, "meteorological variables." Table I lists these variables and defines them. As others could have been chosen, this list serves to define the scope of this discussion.

Table I. Definition of variables.

Roof characteristics

A	thermal diffusivity of plywood sheathing
A'	thermal diffusivity of shingles
c'	composition = asphalt, aluminum, cedar
i	section of roof (E = eave, L = low, M = middle, R = ridge, U = underdeck, F = attic floor)
j	(α, c') = 1 to 6 (1 = low-slope, asphalt roof; 2 = low-slope, aluminum roof; 3 = low-slope, cedar roof; 4 = high-slope, asphalt roof; 5 = high-slope, aluminum roof; 6 = high-slope, cedar roof)
k	thermal conductivity of plywood sheathing
k'	thermal conductivity of shingles
L	length
p	angle (in horizontal plane measured CW) between ridge line and north
S'	solar absorptivity of shingles
W	width
α	slope = low, high (for 16.3°, 39.8°)
τ	thickness of plywood sheathing
τ'	thickness of shingles at butt end

Roof responses

$[T_{ij}; i = E,L,M,R,U,F;$ $j = 1,2,3,4,5,6]$	temperature of the ith section of the jth roof
$[H_{Ej}, H_{Mj}]$	heat flow profile of jth roof
h_j	snow depth of jth roof
γ_j	% of area covered at depth h_j
V_j	volume of meltwater runoff for jth roof
I_j	degree of icing for jth roof 1 means solid layer of ice under snow 0.75 means solid layer of ice beginning to form 0.50 means numerous icicles extending from snow cover or roof covering 0.25 means few small icicles hanging from eave 0 means no visible sign of ice

Meteorological variables

R_n	vertical eppley solar radiation
S	snowfall
t	time of day
T_A	air temperature
ρ_s	density of snow
ρ_w	density of water
v	windspeed

EXPERIMENTAL PROCEDURE

Description of roofs

Two contiguous gable roofs were built on top of a trailer being used as an office at CRREL, Hanover, New Hampshire. These roofs differed in slope but were otherwise constructed the same. The sheathing of the combined roofs was divided into seven identical panels – three of them on the high-slope end and four on the low-slope end. Six of these panels were covered with one of three different roofing materials – cedar shingles, corrugated aluminum sheeting, and asphalt shingles so that six "test roofs" were created. (Hereafter, "roof" will refer to one of these six test roofs.) The seventh panel was provided as a separation to prevent the high-slope roofs from shadowing the low-slope roofs. Figure 1 shows the test roofs shortly after they were constructed. Table II gives their characteristics. The trailer was positioned as shown in Figure 2, which also gives the location of the monitoring stations for the meteorological data. The floor of the attic (originally, the trailer's roof) was insulated with Styrofoam panels and access to the attic was provided by doors built into the gables.

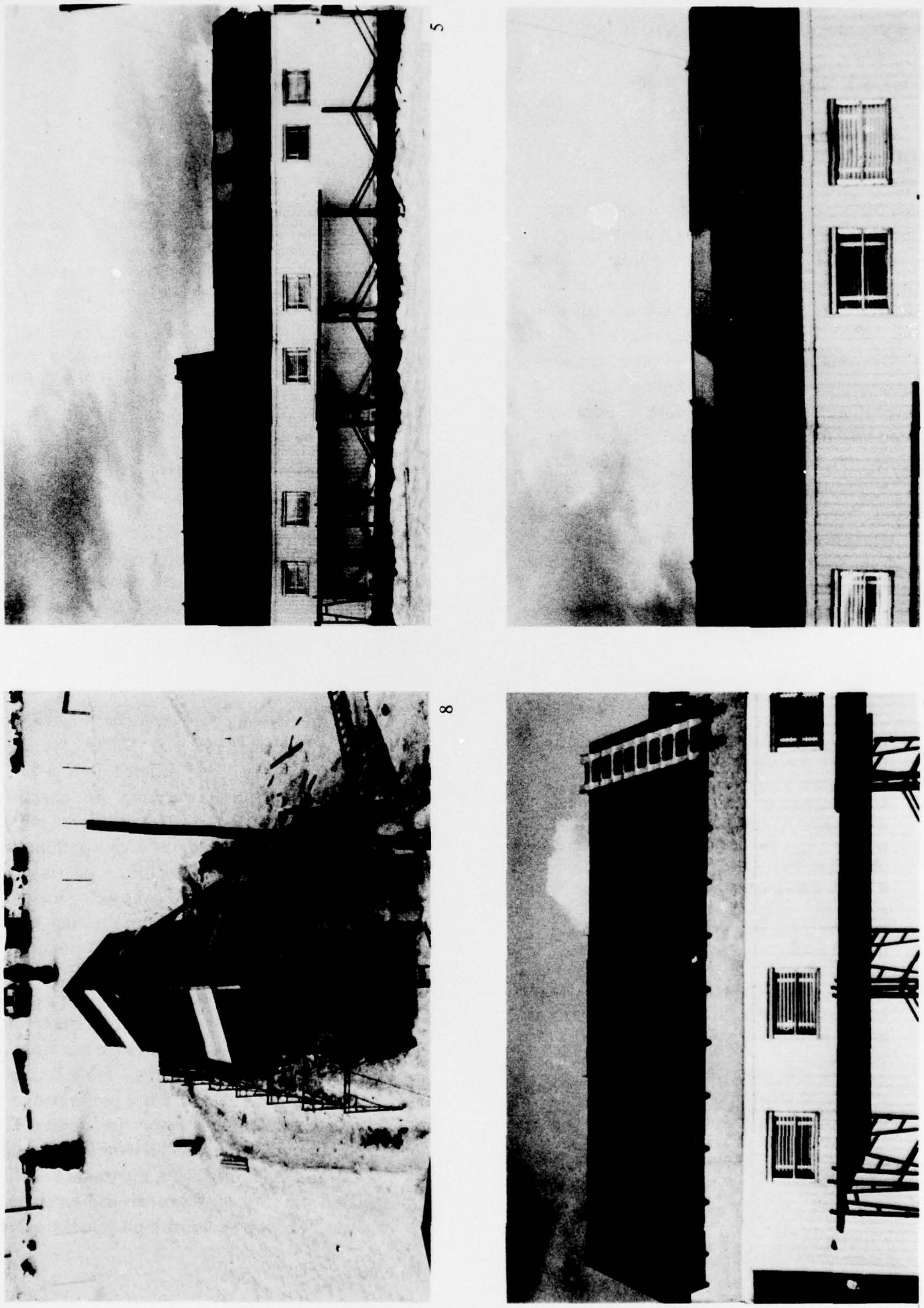


Figure 1. Test roofs as constructed.

Table II. Characteristics of roofs.

α (°)	c'	τ' (cm)	k' (W/m-K)	A' (m²/s×10⁻⁷)	S'	L (m)	W (m)	p (°)	τ (cm)	k (W/mK)	A (m²/s×10⁻⁷)
16.3	Asphalt	0.635	0.145[1]	1.475[3]	0.82 to 0.91[5]	2.438	1.829	43	1.905[1]	0.138[1]	1.59[3]
	Aluminum	0.0381	112 to 229[4]	480 to 946[4]	0.26[6]	2.438	1.829	43	1.905[1]	0.138[1]	1.59[3]
	Cedar	1.27	0.121[2]	1.826[2,3]	0.9[7]	2.438	1.829	43	1.905[1]	0.138[1]	1.59[3]
39.8	Asphalt	0.635	0.145[1]	1.475[3]	0.82 to 0.91[5]	2.438	1.829	43	1.905[1]	0.138[1]	1.59[3]
	Aluminum	0.0381	112 to 229[4]	480 to 946[4]	0.26[6]	2.438	1.829	43	1.905[1]	0.138[1]	1.59[3]
	Cedar	1.27	0.121[2]	1.826[2,3]	0.9[7]	2.438	1.829	43	1.905[1]	0.138[1]	1.59[3]

Definitions:
- A thermal diffusivity of sheathing (plywood)
- A' thermal diffusivity of covering
- c' material used to cover roof
- k thermal conductivity of sheathing (plywood)
- k' thermal conductivity of covering
- L length of roof
- p angle (measured CW in horizontal plane) between ridge line of roof and north
- S' solar absorptivity of covering
- W width of roof
- α slope (16.3° = 3.5 in 12; 39.8° = 10 in 12)
- τ thickness of sheathing (plywood)
- τ' thickness of covering (butt-end of shingles)

Sources:

1. Burch, D.M., B.A. Peavy and F.J. Powell (1975) Comparison between measured computer-predicted hourly heating and cooling energy requirements for an instrumented wood-framed townhouse subjected to laboratory tests. *ASHRAE Trans.*, vol. 81, part II, no. 2363, p. 70-88.
2. Same as (1) but assuming cedar and redwood are similar.
3. Calculated using values in (1) for thermal conductivity, specific heat, and density.
4. Eckert, E.R.G. and R.M. Drake, Jr. (1950) *Introduction to the transfer of heat and mass.* New York, Toronto, London: McGraw-Hill Book Co., Inc., 1st ed., p. 266.
5. Strock, C. and R.L. Koral (Eds.) (1965) *Handbook of air conditioning, heating and ventilating.* New York: Industrial Press, 2nd ed.
6. Brown, A.I. and S.M. Marco (1951) *Introduction to heat transfer.* New York, Toronto, London: McGraw-Hill Book Co., Inc., 2nd ed., p. 68.
7. *ASHRAE handbook of fundamentals* (1974) American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, p. 572. (Assuming that white oak is representative of other woods and that wood is approximately a black body so that emissivity is approximately equal to absorptivity.)

Each test roof was instrumented as follows (see Fig. 3): A calibrated gutter was provided to measure the volume of meltwater runoff. Four thermocouples were installed in the covering material on the southeastern side to measure the temperatures of the eaves T_E, the lower edge of the roof just above the eaves T_L, the middle of the roof T_M, and the ridge of the roof T_R. Another thermocouple was installed under the deck of each roof, directly beneath the thermocouple measuring T_M to measure the under-deck temperature T_U. Two heat flow meters were installed, immediately adjacent to the thermocouples measuring T_E and T_M, and these measured the heat flow through the eaves H_E and the heat flow through the middle of the roof H_M, respectively.

Two additional thermocouples were installed. These were placed immediately above the insulated attic floor so that one was centered in the attic space under the high-slope test roofs and the other was centered under the low-slope test roofs; these thermocouples measured the temperature of the attic floor T_F for the two different slopes.

The cables for the thermocouples and heat flow meters were strung from each test roof to a data logger located in an adjacent building.

Meteorological data

Before 1 November 1972, meteorological data were taken as follows. Solar radiation was measured with a solar radiometer that was mounted on the building housing the data logger. The output of the radiometer was coupled to a strip chart recorder, which plotted a continuous radiation curve as a function of time. These curves were integrated by hand to obtain values of ΣR_n (total radiation energy incident in the vertical direction) for each day. Other

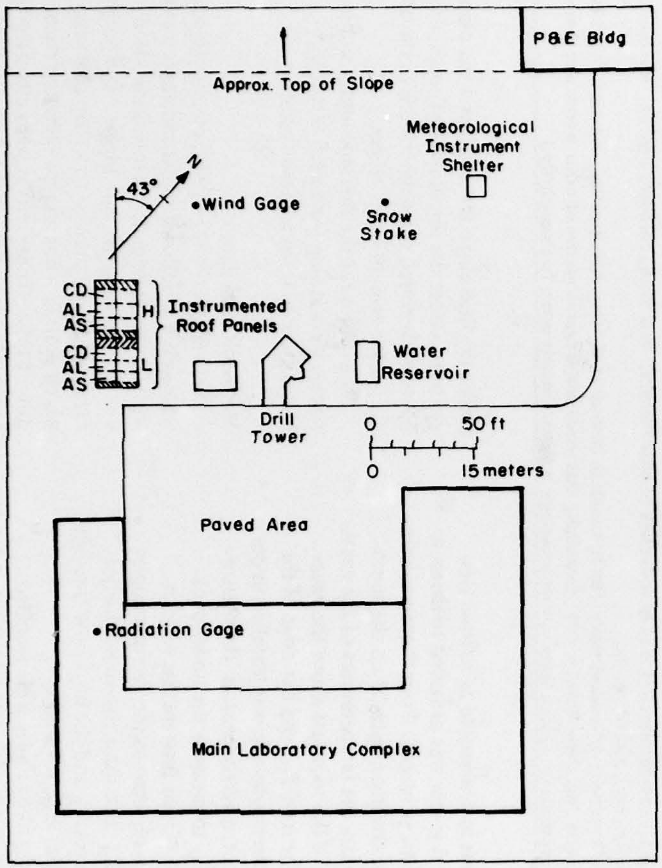


Figure 2. Relative positions of roofs, meteorological stations, adjacent structures, and geographical directions.

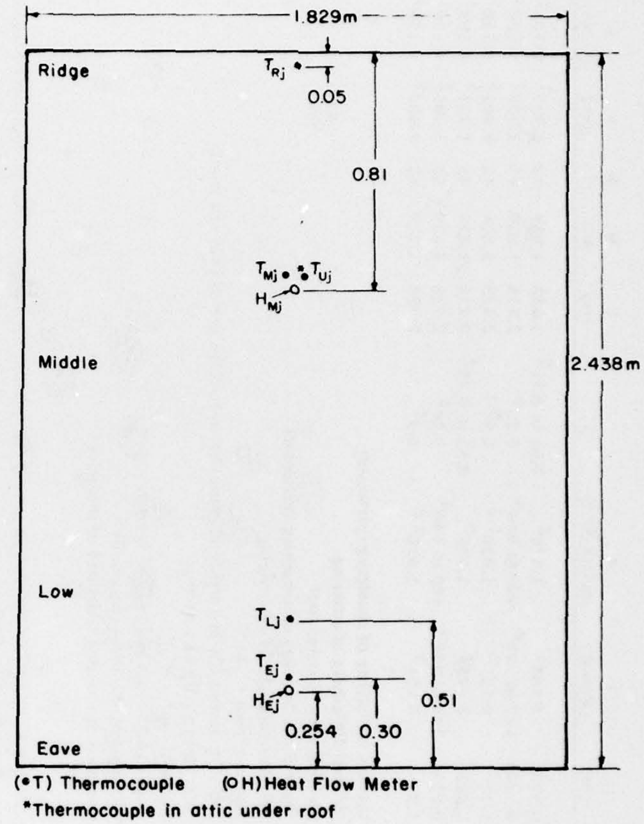


Figure 3. Positions of thermocouples and heat flow meters on the jth roof (see Table I).

Table III. Data for test days of minimum windspeed.

Date	Windspeed v (km/h) Min	Max	Avg	Air temperature T_A (°C) Min	Max	Avg	Snowfall S (cm)	Vertical Eppley solar radiation ΣR_n (MJ/m^2)
23 Dec 72	0	3.22	1.945	- 6.67	- 2.78	- 4.10	16.76	1.46
24 Dec 72	0	6.44	2.28	- 3.61	- 1.39	- 2.78	16.76	2.845
25 Dec 72	0	6.44	3.15	- 1.67	+ 2.22	- 0.24	16.76	0.96
9 Jan 73	0	4.83	2.01	-28.89	-10.00	-20.545	0	8.20
13 Jan 73	0	3.22	1.94	-21.11	- 4.17	-13.46	0	9.83
14 Jan 73	0	8.05	2.415	-17.22	0.00	- 6.39	0	4.895
15 Jan 73	0	4.83	2.49	- 4.72	+ 4.17	- 0.60	0	5.48

Date	Snow depth of jth roof (cm) h(j = 1)	h(j = 2)	h(j = 3)	h(j = 4)	h(j = 5)	h(j = 6)
23 Dec 72	1.3	1.3	1.3	1.3	1	1.3
24 Dec 72	1.3	1.3	1.3	1.3	1	1.3
25 Dec 72	1.3	1.3	1.3	1.3	1	1.3
9 Jan 73	21.6	23.5	30.5	14.6	0	14.6
13 Jan 73	21.6	23.5	30.5	13.0	0	14.0
14 Jan 73	21.6	23.5	30.5	13.0	0	14.0
15 Jan 73	20.95	22.9	29.8	12.7	0	12.7

Date	Snow coverage of jth roof (%) γ(j = 1)	γ(j = 2)	γ(j = 3)	γ(j = 4)	γ(j = 5)	γ(j = 6)
23 Dec 72	100	100	100	100	100	100
24 Dec 72	100	100	100	100	100	100
25 Dec 72	100	100	100	100	100	100
9 Jan 73	87.5	87.5	87.5	81	0	81
13 Jan 73	87.5	87.5	87.5	81	0	81
14 Jan 73	87.5	87.5	87.5	81	0	81
15 Jan 73	87.5	87.5	87.5	81	0	81

meteorological data were taken from the records kept at Lebanon Airport, West Lebanon, N.H. (13 km to the south), and Dartmouth College, Hanover, N.H. (1.6 km to the south).

After 1 November 1972, hourly, on-site data for all meteorological variables were provided by a meteorological team attached to the U.S. Army Electronics Command and stationed at USACRREL, Hanover, N.H.

Procedure

Data were collected from 3 December 1971 to 20 March 1972 and from 28 November 1972 to 30 March 1973. Thermocouple and heat flow meter data were automatically recorded on an hourly basis. Meteorological data were recorded on a daily basis before 1 November 1972 and, after that date, on an hourly basis. Meltwater runoff volumes were recorded as necessary to prevent overflow of the gutter. Snow depth measurements were made daily on each roof immediately following each snowfall. Color slides (35-mm camera, Kodachrome film) were taken at regular intervals to record the coverage γ, the degree of icing I, and the chronological history of the snow cover for each roof from snowfall to snowfall.

ANALYSIS

General

The approach was to consider the meteorological variables as interacting with the roof characteristics to produce the roof responses. From this point of view, it was necessary to attempt to "separate variables." The meteorological data were sorted to select seven test days for which the windspeed ν was the lowest of all the test days. This was assumed to minimize the wind effects on the selected days, thus allowing a study of the effects of solar radiation. The values of the meteorological variables for the selected test days are given in Table III.

Table IV. Frequency of temperature profiles: In each profile expression, temperature increases from left to right and indices in parentheses indicate equal temperatures.

1 (L,ASP)		2 (L,ALM)		3 (L,CDR)		4 (H,ASP)	
Profile	No. of test hours	Profile	No. of test hours	Profile	No. of test hours	Profile	No. of test hours
E(LMR)UF	47	ERLMUF	21	EL(MR)UF	68	E(LM)UF	57
ER(LM)UF	30	(EL)(MR)UF	20	ELRMFU	30	ELMUF	56
ERMLUF	27	E(LMR)UF	19	EL(MR)FU	27	(ELM)UF	18
(ELMR)UF	23	E(LR)MUF	13	ELRFMU	8	(MUFLE	8
E(LR)MUF	7	E(LM)(RU)F	10	ELR(MF)U	6	MLUFE	5
M(LR)UFE	5	ER(LM(UF	10	RMLEFU	5	M(UF)LE	3
(LMR)UFE	3	ELRMUF	10	RMLFEU	4	(EL)MUF	2
(LM)RUFE	3	EL(MR)UF	10	E(LMR)UF	3	EL(MUF)	2
R(LM)UFE	3	E(LM)URF	9	EL(MR)(UF)	3	EL(MU)F	2
(ER)(LM)UF	2	(ELR)MUF	7	RMLFUE	3	MFULE	2
L(MR)UFE	2	LMRUFE	7	(ER)LMFU	2	MU(LF)E	2
MLRUFE	2	(ELM)URF	6	ELRUMF	1	MULFE	2
RMLUFE	2	LMREUF	6	(ER)(LM)FU	1	ELU(MF)	1
R(LM)EUF	2	LMRUEF	3	ELMR(UF)	1	EM(UF)L	1
(EL)(MR)UF	1	E(LM)RUF	2	(ELR)MFU	1	EMU(LF)	1
(ER)LMUF	1	(LR)MEUF	2	(EL)(MR)FU	1	LM(EU)F	1
EL(MR)UF	1	LEMRUF	2	(EL)(MR)(UF)	1	LMUFE	1
(LR)MUFE	1	(ER)(LM)UF	1	(MR)(EL)FU	1	(LM)UEF	1
(LR)MEUF	1	ERMLUF	1	R(LM)EFU	1	MLEUF	1
LMRUFE	1	ELMRUF	1	R(ELM)FU	1	M(LU)FE	1
LMREUF	1	LMR(EU)F	1			MLU(EF)	1
(MR)LEUF	1	L(MR)(EU)F	1				
(MR)L(EU)F	1	L(MR)UFE	1				
R(LM)UEF	1	LMERUF	1				
		L(EM)RUF	1				
		R(LM)UEF	1				
		RELMUF	1				
		R(EL)MUF	1				

5 (H,ALM)				6 (H,CDR)			
Profile	No. of test hours	Profile	No. of test hours	Profile	No. of test hours	Profile	No. of test hours
E(LR)UMF	30	(ELMU)(RF)	1	ELM(RU)F	54	ERMLUF	1
ELRUMF	25	(EL)(MU)RF	1	ERLMUF	34	L(MR)UEF	1
(ELU)MRF	20	ERLUMF	1	ELMRUF	22	(LM)RUFE	1
E(LU)MRF	18	EL(MRU)F	1	ER(LM)UF	6	LM(RU)EF	1
E(LU)(MR)F	14	(LR)UEMF	1	MLUFRE	6	(LM)ERUF	1
FMULRE	10	(LR)(EMU)F	1	EL(MR)UF	5	L(EM)RUF	1
(EL)UMRF	7	MU(ELF)R	1	LMRUEF	3	(LM)(RU)EF	1
E(LRU)MF	6	M(EL)UFR	1	ERMULF	2	(LM)UREF	1
EL(RU)MF	6	MF(ELU)R	1	(LM)URFE	2	M(LRU)FE	1
EL(MU)RF	3	(MUF)(LR)E	1	(LM)(ER)UF	2	MLU(RF)E	1
E(LU)RMF	2	MFULER	1	(LMR)EUF	2	MULRFE	1
(ELU)(MR)F	2	(MF)(LU)RE	1	ML(ERU)F	2	(MR)ULFE	1
ELU(MR)F	2	R(EL)UMF	1	R(MU)LFE	2	MLU(ER)F	1
(MF)ULRE	2	FMUL(ER)	1	(EL)MRUF	1	R(MU)E(LF)	1
(MF)(LU)(ER)	2	F(MU)RLE	1	ELMURF	1	RE(MU)(LF)	1
(ER)(LU)MF	1	FM(LU)(ER)	1	(ER)MU(LF)	1	RMULFE	1
(EL)U(MR)F	1	FM(LU)RE	1	ER(MU)(LF)	1	RM(LU)EF	1
				(ER)(LM)UF	1	REMULF	1
				E(LR)MUF	1	R(ELM)UF	1
				(ELM)RUF	1		

Table V. **Maximum temperature profiles. In each profile expression, temperature increases from left to right.**

Roof, j	Maximum Profile	No. of test hours	Observed Members of Compatible Set
1	ERMLUF	129	E(LMR)UF, ER(LM)UF, ERMLUF, (ELMR)UF, (ER)(LM)UF
2	ELRMUF*	79	(EL)(MR)UF, E(LMR)UF, E (LR)MUF, ELRMUF, EL(MR)UF, (ELR)MUF
	ERLMUF	71	ERLMUF, E(LMR)UF, E(LR)MUF, ER(LM)UF, (ELR)MUF, (ER)(LM)UF
3	ELMRUF*	76	EL(MR)UF, E(LMR)UF, EL(MR)(UF), ELMR(UF), (EL)(MR)(UF)
	ELRMUF	75	EL(MR)UF, E(LMR)UF, EL(MR)(UF), (EL)(MR)(UF)
	ELRMFU	69	ELRMFU, EL(MR)FU, ELR(MF)U, EL(MR)(UF), (ELR)MFU, (EL)(MR)FU, (EL)(MR)(UF)
4	ELMUF	137	E(LM)UF, ELMUF, (ELM)UF, (EL)MUF, EL(MUF), EL(MU)F
5	ELUMRF*	70	(ELU)MRF, E(LU)MRF, E(LU)(MR)F, (EL)UMRF, EL(MU)RF, (ELU)(MR)F, ELU(MR)F, (EL)U(MR)F, (ELMU)(RF), (EL)(MU)RF, EL(MRU)F
	ELRUMF	68	E(LR)UMF, ELRUMF, E(LRU)MF, EL(RU)MF, EL(MRU)F
6	ELMRUF	83	ELM(RU)F, ELMRUF, EL(MR)UF, (EL)MRUF, (ELM)RUF

*Significant observations of competing profiles make this identification as "maximum" unsure. In these cases, the competing profiles are given below the tentative maximum profile.

Temperature profiles

For a given roof *j* and a given hour of the day *t*, the temperatures T_{Ej}, T_{Lj}, T_{Mj}, T_{Uj}, and T_{Fj} (where the indices refer to the roof section and roof as defined in Table I) were compared to provide a "profile" of the roof for that hour. The profile was symbolized by writing the indices *E, L, M, R, U,* and *F* in the order of increasing temperature values with equal temperatures represented by parentheses around the relevant indices. For example, "*FL(UR)ME*" meant that, on a given day at a given hour for roof *j*, $T_{Fj} < T_{Lj} < T_{Uj} = T_{Rj} < T_{Mj} < T_{Ej}$. These profiles were used as convenient shorthand to display the manner in which the different parts of a roof changed in temperature relative to each other as the solar radiation changed. Profiles were written for each roof and each of the 168 hours of the seven test days. For each roof, the number of hours for which each profile was observed was counted. Table IV lists the profiles observed and their frequency for each roof.

Once the distribution of profiles had been obtained, this distribution was analyzed to determine the profile containing no equalities that most nearly accounted for all the profiles observed for a given roof. For example, Table IV shows that the profiles *(EL)(MR)UF*, *E(LMR)UF*, *E(LR)MUF*, *E(LM)(RU)F*, *ELRMUF*, *EL(MR)UF*, and *(ELR)MUF* are all compatible in that, for the equalities, the order of indices is immaterial. This entire set of profiles can be represented by *ELRMUF*, the member with no equalities. All of the possible compatible sets of this sort were assembled for each roof and the total numbers of observations for each counted. (To distinguish these sets of profiles from the profile that is only a member of the set, the profile expression was underlined when it referred to the compatible set.) The compatible set with the largest number of hours of observation was termed the "maximum profile" for the roof. Table V lists the maximum profiles for the six test roofs.

Table VI. Temperature profile variation with solar radiation.

The "most likely" profile for each hour of a day is compared with the values of the hourly solar radiation for 14 January 1973. (The total daily solar radiation was a median value for 14 January 1973 as compared with the other six test days.) In each profile expression, temperatures increased from left to right.

	MOST LIKELY PROFILES FOR jth ROOF						
	1	2	3	4	5	6	R_n
Hour	(L,ASP)	(L,ALM)	(L,CDR)	(H,ASP)	(H,ALM)	(H,CDR)	MJ/m^2
0100	ERMLUF	ERLMUF	ELRMFU	ELMUF	ELRUMF	ERLMUF*	0
0200	"	ELRMUF	" *	"	"	"	"
0300	"	ERLMUF	" *	"	"	"	"
0400	"	"	" *	"	"	"	"
0500	"	"	" *	"	"	"	"
0600	"	"	" *	"	"	"	"
0700	"	"	" *	"	"	"	"
0800	"	ELRMUF*	" *	"	"	"	0.25
0900	"	" *	"	"	ELUMRF	ELMRUF	0.29
1000	"	"	"	"	"	"	0.54
1100	" *	ELMURF	ELMRUF	" *	"	"	0.83
1200	" *	"	"	MUFLE	FMULRE	"	0.96
1300	" *	" *	"	" *	"	"	0.63
1400	" *	" *	"	" *	"	"	0.54
1500	"	"	"	ELMUF	"	"	0.50
1600	"	"	"	"	ELUMRF	"	0.25
1700	"	ELRMUF	"	"	"	"	0.08
1800	"	"	"	"	" *	"	0
1900	"	ERLMUF*	"	"	ELRUMF	"	"
2000	"	" *	" *	"	"	"	"
2100	"	"	ELRMFU	"	"	"	"
2200	"	ELRMUF	"	"	"	"	"
2300	"	"	"	"	"	"	"
2400	"	ERLMUF*	"	"	"	"	"

* Significant observations of competing profiles make this identification as "most likely" unsure.

The profiles were then considered by time of day for each roof. For each hour of the day and a given roof, a profile for each of the seven test days was written. The compatible set to which most of these seven profiles belonged was then termed the "most likely profile" for that roof at that time of day. For example, if the low-slope aluminum roof exhibited the following profiles at 0800 hours on the seven test days: *(ELR)MUF*, *ELRMUF*, *ERLMUF*, *ERLMUF*, *ELRMUF*, *ELRMUF*, and *(EL)(MR)UF*, the most likely profile for this roof at 0800 hours was *ELRMUF*. The results of this analysis are given in Table VI, which displays the most likely profiles as a function of roof, time of day, and solar radiation.

Temperature rankings

For a given section i of a roof and a given hour of the day, the temperatures T_{i1}, T_{i2}, T_{i3}, T_{i4}, T_{i5}, and T_{i6} (where the numerical indices now refer to the roof number j as defined in Table I) were compared to provide a "ranking" of the roofs for that section at that hour of that day. These rankings were expressed in a manner analogous to that discussed above for profiles and analyzed in the same manner to find the maximum ranking for a roof part and the most likely ranking for a roof part at a given time of day. For example, the ranking 126543 meant that $T_{i1} < T_{i2} < T_{i6} < T_{i5} < T_{i4} < T_{i3}$ and the ranking 126543 represented a set of rankings compatible with 126543.

Table VII. Frequency of temperature rankings for *i*th roof section.

The lists of rankings have been abbreviated to give only the first 16 rankings in order of decreasing frequency. This is sufficient to account for at least 50% of the data hours.

E = EAVES Ranking	No.	L = LOW Ranking	No.	M = MIDDLE Ranking	No.	R = RIDGE Ranking	No.
(654321)	16	(654321)	23	(421)3(65)	56	13265	23
3(65421)	9	5463(21)	13	(421)365	7	65123	21
(64321)5	8	2(65431)	13	(64)1(52)3	5	(21)356	15
326514	7	(64321)5	10	(64)5123	5	1(32)65	9
(632)(541)	5	(21)6345	8	64(51)23	5	56123	8
362514	5	3(65421)	5	5(64)123	5	(65)123	6
(6432)(51)	4	216345	4	(421)(53)6	5	6(51)23	6
(63)(5421)	4	(32)(6451)	4	6(41)523	4	213(65)	6
(632)(41)5	4	(54321)6	4	6(41)2(53)	3	(21)3(65)	6
415263	4	4(653)(21)	4	(61)2435	3	132(65)	5
451236	3	32(6541)	3	6(41)(52)3	3	123(65)	5
3(61)(542)	3	(543)621	3	6(421)35	3	12365	4
31(6542)	3	(543)6(21)	3	641253	2	16235	4
36(5421)	3	546312	3	(64)1253	2	(65)(21)3	3
3(6421)5	3	54(21)36	3	6(541)23	2	65(21)3	3
3(62)514	3	(62)(431)5	3	6(41)235	2	(61)(52)3	3
others	84	others	62	others	56	others	41

U = UNDER DECK Ranking	No.	F = FLOOR Ranking	No.
564123	43	(654)(321)	95
524(61)3	11	(654321)	57
564(21)3	11	(321)(654)	16
5(42)(61)3	8		
54(21)63	8		
54(621)3	7		
54(21)(63)	7		
(65)4123	6		
52(41)63	5		
5(42)163	5		
61(42)35	4		
641253	4		
(542)(61)3	4		
641235	3		
5(42)1(63)	3		
5421(63)	3		
others	36		

It should be noted at this point that, for the floor of the roof, only two thermocouples were installed so that the high-slope and the low-slope roofs could be distinguished but not the individual high-slope roofs or the individual low-slope roofs. That is, for the floor ($i = F$), there were only three possible rankings: (321)(654), (654)(321), and (654321).

Table VII gives an abbreviated listing of the observed rankings for each roof section. Table VIII lists the maximum rankings for each roof section and the most likely rankings are given in Table IX as a function of the hour of the day and the solar radiation.

A comparison of Tables IV, V and VI with Tables VII, VIII, and IX immediately indicates that the interpretation of the variation for a given roof is more straightforward than that for the variation for a given roof section. This is because, in the latter case, there are competing effects of roof covering composition c' and roof slope α. The effects of these two roof characteristics must be separated.

To determine the relative effects of the roof characteristics α and c', Tables X and XI were constructed. Table X gives the percentage of the total number of test hours for which each of the possible ranking equalities was observed for a given roof section. This displays which roofs tend to behave alike for a given roof section and should reveal effects due to composition. Table XI was constructed by first eliminating all those rankings for which the presence of equalities made it unclear whether the high-slope roofs as a group were lower or higher in temperature for the given roof section than

Table VIII. Maximum temperature rankings.

ith Section	Maximum Ranking	No.	Observed Members of Compatible Set
E = Eaves	362415	61	(654321), 3(65421), (64321)5, (632)(541) (6432)(51), (63)(5421), (632)(41)5, 36(421)5, 3(62)(541), 3(642)(51)
L = Low	216345	62	(654321), 2(65431), (64321)5, (21)6345, 216345, (621)345, 2163(54), 2(6431)5
M = Middle	(421)365	64	(421)3(65), (421)365, (421)(63)5
R = Ridge*	65123	40	65123, (65)123, 6(51)23, (65)(21)3, 65(21)3, (651)23
	13265	39	13265, 1(32)65, 132(65), 1(632)5
U = Under deck	564123	63	564123, 564(21)3, (65)4123, 56(41)23
F = Floor	(654)(321)	95	(654)(321)

*More than one set included due to lack of distinction in number of observed hours of data.

the low-slope roofs. The remaining rankings were divided into three groups: those with all high-slope roofs having higher temperatures than all the low-slope roofs, those for the reverse case, and those for which neither case was true. This displays effects due to the slope of the roof.

Heat flow

The net heat accumulated per unit area in the time period t_1 to t_2 by the eave (or middle) sections was calculated from the heat flow meter data for the seven test days by use of the approximation:

$$\left(\frac{\text{net heat}}{\text{unit area}}\right)_E \equiv \int_{t_1}^{t_2} H_E\,dt \cong \sum_{t=t_1}^{t_2} [(1\text{ hr})H_E(t)] \qquad (1)$$

where $H_E(t)$ is the value of H_E that was measured at the beginning of hour t. [The equivalent expression for the middle section is achieved by substituting H_M and $H_M(t)$ for H_E and $H_E(t)$.] This approximation means to assume that the heat flow H_E (or H_M) remained constant during any given test hour. Equation 1 is written so that net heat flow into the eaves (or middle) section of a roof will be indicated by a positive value of $\int H_E dt$ (or $\int H_M dt$). The net heat flows $\int H_E dt$ and $\int H_M dt$ were calculated for three specific time periods t_1 to t_2, 0000 to 0800 hours, 0800 to 1700 hours, and 1700 to 2400 hours, of two representative test days. The results are given in Table XII along with the relevant meteorological data and the corresponding average temperatures of the eaves and middle roof sections.

Snow depths and meltwater volumes

The snow depths h_1, h_2, h_3, h_4, h_5 and h_6 (where the indices refer to the particular test roof) that were observed on the roofs are given in Table XIII and the corresponding percentages of cover γ_1, γ_2, γ_3, γ_4, γ_5, and γ_6 are given in Table XIV.

The fraction of the original snow cover that was collected as meltwater volumes V_1, V_2, V_3, V_4, V_5 and V_6 where the indices again refer to the test roofs was calculated by assuming that the original snow cover had a density of 0.2 g/cm^3 and had a uniform thickness.[3] "Original snowfall" is the snowfall occurring in such close proximity in time as to be undissipated at the time of the first measurements of snow depths and coverages following its cessation. The meltwater volumes were measured whenever the practical requirements of using the calibrated gutters made it necessary. With these assumptions, the meltwater fraction of the original snow cover could be calculated for each roof from

Table IX. Temperature ranking variation with solar radiation.

The "most likely" ranking for each hour of a day is compared with the values of the hourly solar radiation for 14 January 1973. (The total daily solar radiation was a median value for 14 January 1973 as compared to the other six test days.)

Hour	MOST LIKELY RANKINGS FOR ith ROOF SECTION						R_n MJ/m^2
	E=Eaves	L=Low	M=Middle	R=Ridge	U=Under	F=Floor	
0100	451632	546321	(421)3(65)	65123	564123	(654)321)	0
0200	"	"	"	"	"	"	"
0300	416352	"	"	"	"	"	"
0400	415632	"	"	"	"	"	"
0500	"	"	"	"	"	"	"
0600	164352	"	"	"	"	"	"
0700	"	"	"	" *	"	"	"
0800	163425	"	"	132(65)	"	"	0.25
0900	362415	"	"	"	"	"	0.29
1000	362154	"	"	"	524163*	"	0.54
1100	"	621345	" *	16235	"	"	0.83
1200	"	"	"	13265	641235	"	0.96
1300	"	216345	"	"	614235	"	0.63
1400	"	"	"	"	"	" *	0.54
1500	326514	"	"	"	"	" *	0.50
1600	326415	"	"	" *	524163	"	0.25
1700	324165	"	"	12365	" *	"	0.08
1800	324615	"	"	"	564123	"	0
1900	326415	"	"	"	"	"	"
2000	412536	"	"	"	"	"	"
2100	326415	"	"	65123	"	"	"
2200	415263	"	"	"	" *	"	"
2300	145263	"	"	"	"	"	"
2400	415623	"	"	"	"	"	"

* Significant observations of competing rankings make this identification as "most likely" unsure.

$$\frac{\text{Meltwater}}{\text{Snow cover}}_{\text{roof no.}} \cong \frac{1}{0.2}\,(100\,V/\gamma L W h)_{\text{roof no.}} \qquad (2)$$

and the results are listed along with the relevant meltwater volumes in Table XV. In eq 2, L and W are the common length and width of the test roofs (refer to Table II); the other variables are meltwater volume V, coverage γ, and snow-depth h, which are functions of the particular roof and meteorological variables.

In Table XV, all data are keyed to the "original snowfall." Upon cessation of a snowfall, measurements of h and γ for each roof were made at intervals to provide a record of the changing conditions on the roofs following snowfall. The values of h and γ that were used in eq 2 to compute meltwater fractions were those measured immediately after cessation of the snowfall before significant dissipation had occurred. Depending upon meteorological conditions, the calibrated gutters required emptying at differing frequencies for different snowfalls. The meltwater fractions and volumes recorded in Table XV represent the total meltwater fraction for the particular snowfall: The relevant values of V for each roof were determined by adding all of the meltwater volumes collected for a given roof subsequent to the given snowfall. The dates

Table X. Effects due to composition of roof covering.

For each section, the percentage of test hours for which the given roofs were equal in temperature is displayed. The equal temperature roofs are indicated by the equality portions of rankings. All possibilities for equalities are listed.

Partial Ranking	PERCENT OF TEST HOURS OBSERVED FOR ith ROOF SECTION					
	E=Eaves	L=Low	M=Middle	R=Ridge	U=Under	F=Floor
(654321)	9.5	14.0	0	0	0	34.0
(65432)	"	"	"	"	"	"
(65431)	10.0	21.0	"	"	"	"
(65421)	15.0	18.0	"	"	"	"
(65321)	14.0	20.0	"	"	"	"
(54321)	11.0	16.0	"	"	"	"
(6543)	10.0	23.0	"	"	"	"
(6542)	17.0	19.0	"	"	"	"
(6541)	15.0	27.0	0.5	"	"	"
(6532)	11.0	15.0	0	"	"	"
(6531)	10.0	22.0	"	"	"	"
(6432)	18.0	20.0	"	"	"	"
(6431)	15.0	28.0	"	"	"	"
(5432)	11.0	17.0	"	"	"	"
(5431)	"	26.0	"	"	"	"
(4321)	16.0	23.0	"	"	"	"
(5321)	11.0	17.0	"	"	"	"
(5421)	20.0	21.0	"	"	0.5	"
(6321)	15.0	20.0	"	"	0	"
(6421)	21.0	24.0	"	"	"	"
(6521)	15.0	19.0	"	"	"	"
(654)	17.0	31.5	1.0	"	"	100.0
(643)	19.0	30.0	0	"	"	34.0
(632)	26.0	23.0	"	1.0	"	"
(621)	23.0	26.0	"	"	5.0	"
(653)	12.0	24.0	"	0	0	"
(652)	18.0	20.0	"	0.5	"	"
(651)	15.0	31.0	1.0	"	"	"
(642)	28.5	25.0	"	0	"	"
(641)	23.0	37.0	2.0	"	0.5	"
(631)	15.0	28.5	0	"	"	"
(543)	11.0	31.5	"	"	0	"
(542)	24.0	2.1	"	"	5.0	"
(541)	25.0	35.0	2.0	"	0	"
(532)	15.0	18.0	0	"	"	"
(531)	11.0	27.0	"	"	"	"
(521)	20.0	21.0	"	0.5	1.0	"
(432)	21.0	23.0	"	0	0	"
(431)	22.0	37.0	"	"	"	"
(421)	29.0	29.0	45.0	"	1.0	"
(321)	17.0	25.0	0.5	"	0	100.0
(65)	22.0	36.0	37.0	20.0	3.5	100.0
(64)	33.0	42.0	15.0	0	0.5	"
(63)	"	40.0	3.0	2.0	11.0	34.0
(62)	40.0	34.5	4.0	5.0	5.0	"
(61)	28.5	39.0	8.0	"	21.0	"
(54)	32.0	46.0	3.0	0	7.0	100.0
(53)	20.0	37.0	8.0	4.0	0.5	34.0
(52)	33.0	23.0	6.0	"	7.0	34.0
(51)	31.0	36.0	8.0	6.5	2.0	"
(43)	21.0	44.0	2.0	0	0	"
(42)	38.0	30.0	49.0	"	19.0	"
(41)	42.0	45.0	57.0	"	10.0	"
(32)	35.0	25.0	2.0	6.5	0	100.0
(31)	17.0	40.0	0.5	0	0.5	"
(21)	32.0	55.0	46.0	22.0	24.0	"

Table XI. Effects due to slope of roof.

For each section, the percentage of test hours for which the high-slope roofs as a group were definitively lower or higher in temperature than the low-slope roofs as a group is tabulated. All data for which the presence of equal temperatures made it unclear whether the high-slope or low-slope roofs were higher in temperature were excluded from consideration.

Roof section	PERCENT OF TEST HOURS OBSERVED		
	High-slope higher	Low-slope higher	Equal
Eaves	0	0	9.5
Low	28.0	0	14.9
Middle	11.0	0	0
Ridge	27.0	51.0	0
Under	42.0	0	0
Floor	56.5	9.5	34.0

given are those spanning the time from cessation of the snowfall to dissipation of the snow/ice from the roofs or the beginning of a new snowfall, whichever applied. The average total solar radiation for this period is also given.

Degree of icing

A semi-quantitative estimate of the degree of icing I was made by using the definition of I in Table I to analyze the chronological sequence of photographic data. The results of this analysis are in Table XVI. The relevant photographs are illustrated in Figure 4.

RESULTS AND CONCLUSIONS

General

In all discussion below, the test roofs will be identified both descriptively and numerically as in the expression "no. 3 (low-slope, cedar) roof." For more detailed information, refer to Tables I and II.

Individual results will be recounted followed by a discussion relating them to the icing problem.

Temperature profiles of the roofs

Analysis of the results compiled in Table IV allows the roofs to be ordered according to the stability of their temperature profiles, i.e., their ability to maintain the same temperature profile. In order of decreasing stability:

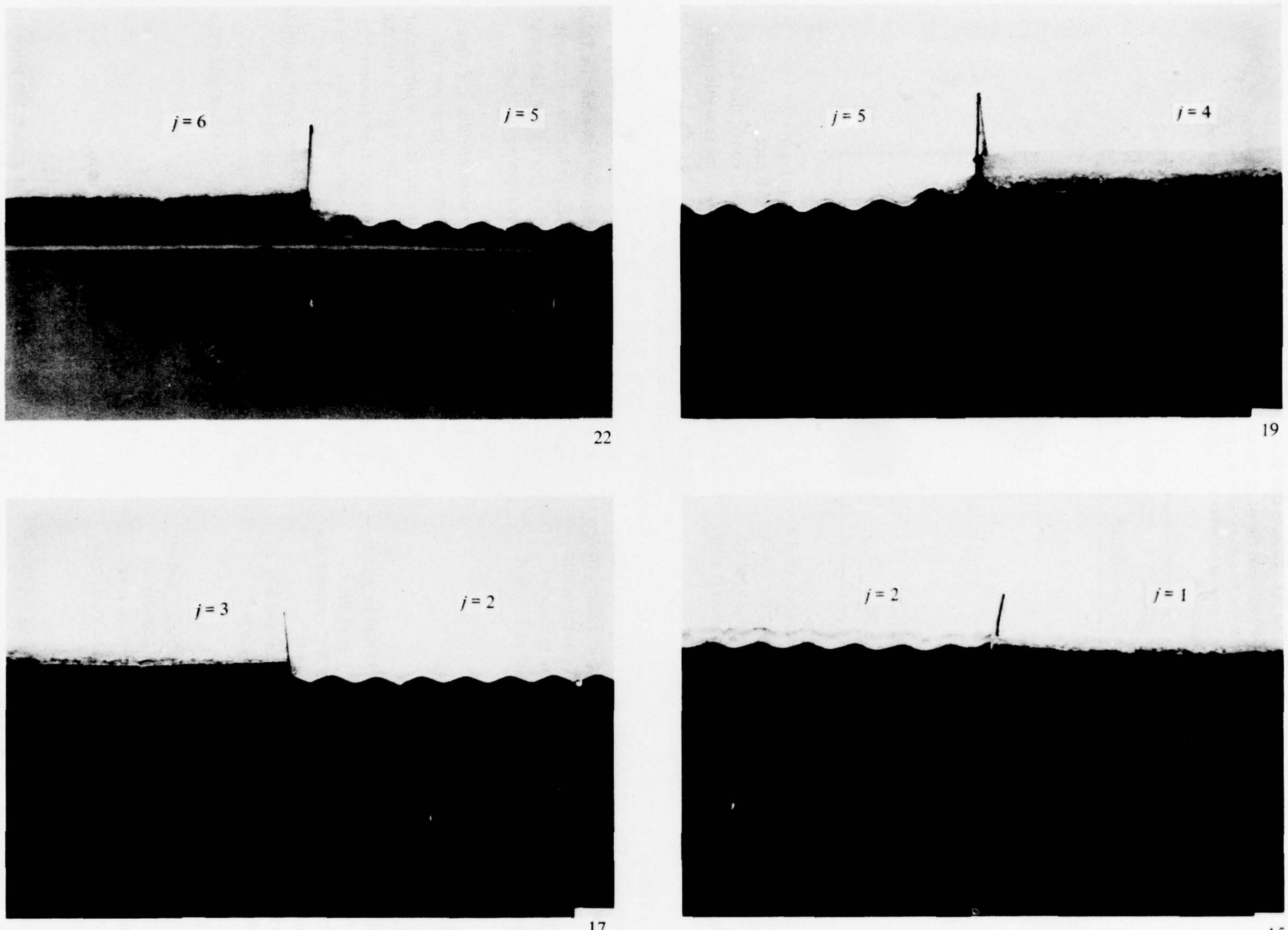
no. 3 (low-slope, cedar) roof
no. 4 (high-slope, asphalt) roof
no. 6 (high-slope, cedar) roof
no. 1 (low-slope, asphalt) roof
no. 5 (high-slope, aluminum) roof
no. 2 (low-slope, aluminum) roof

With the exception of the cedar roofs, this order implies that higher slope leads to a more stable temperature profile. The reason that the cedar roofs fail to display the same slope dependence is that the no. 3 (low-slope, cedar) roof was the only roof that retained a deep enough snow cover (approaching 30 cm) to screen the effects of solar radiation.[5] A study of Table II will reveal that the cedar shingles have the thickest butt end, τ', and therefore, for a given slope, the greatest ability to retain snow cover from a purely geometrical view.

The stability of the temperature profiles as defined above does not take into account how great are the changes in temperature profile; that is, how significant are the changes in profile irrespective of how often the changes take place? This question can be answered by using the concept of compatible sets of profiles. Those profiles belonging to a compatible set are not significantly different. The maximum profiles are compatible sets most often observed. Table V records the maximum profiles and may be used to obtain an ordering of the roofs according to their ability to maintain compatible temperature profiles:

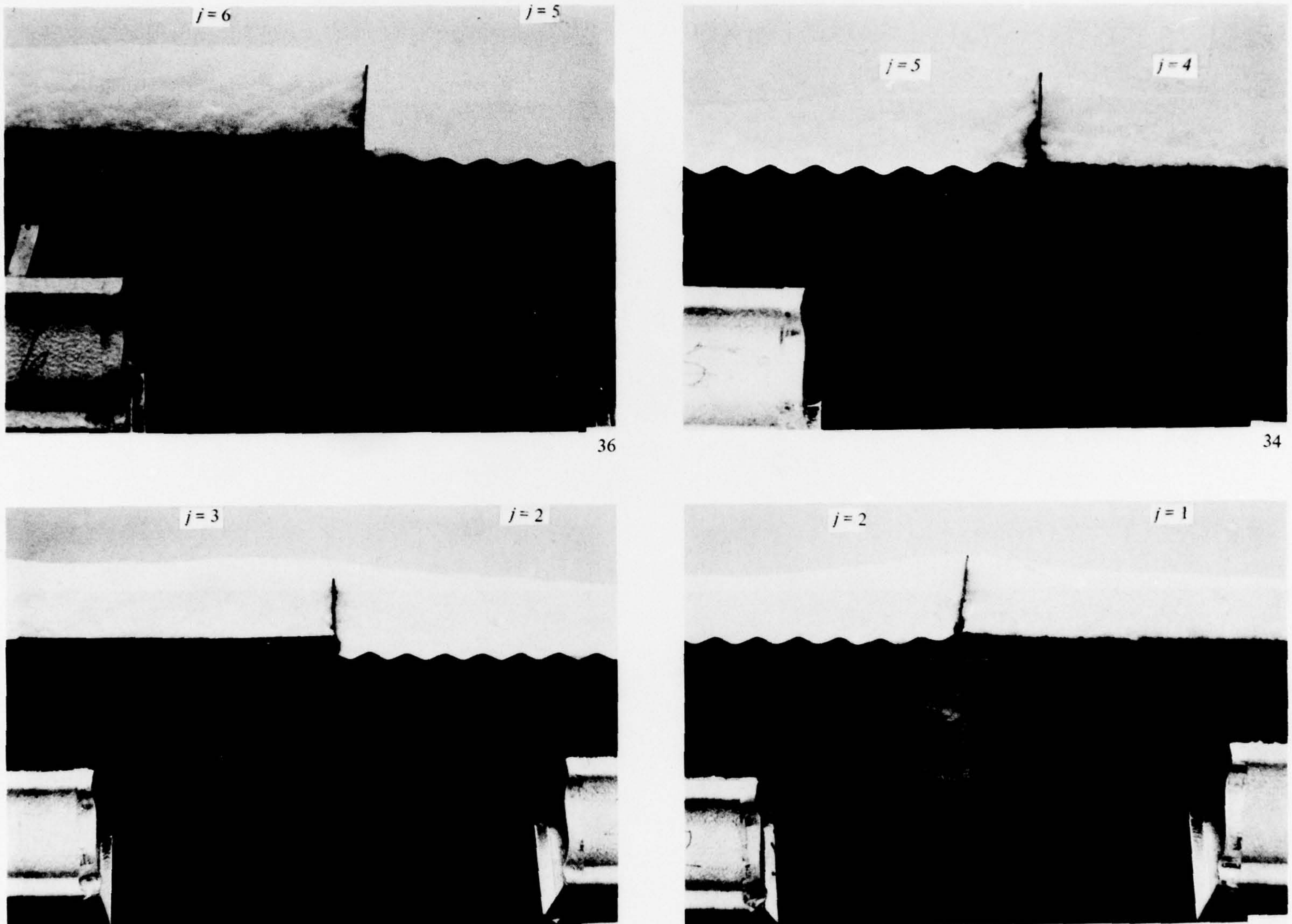
no. 4 (high-slope, asphalt) roof
no. 1 (low-slope, asphalt) roof
no. 6 (high-slope, cedar) roof
no. 2 (low-slope, aluminum) roof
no. 3 (low-slope, cedar) roof
no. 5 (high-slope, aluminum) roof

Again, the results imply that the greater the slope, the greater the ability to maintain a temperature profile within a narrow range of change. This time, it is



4a. 0830, 7 Dec 71.

Figure 4. Photographs displaying relative icing of the roofs.

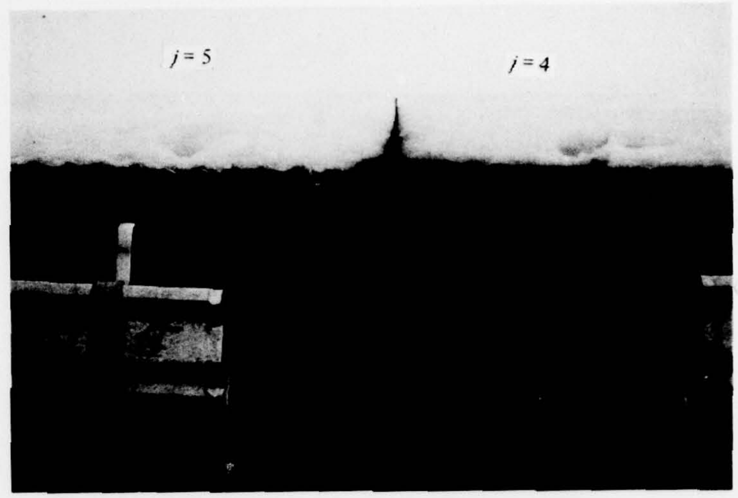


36 34

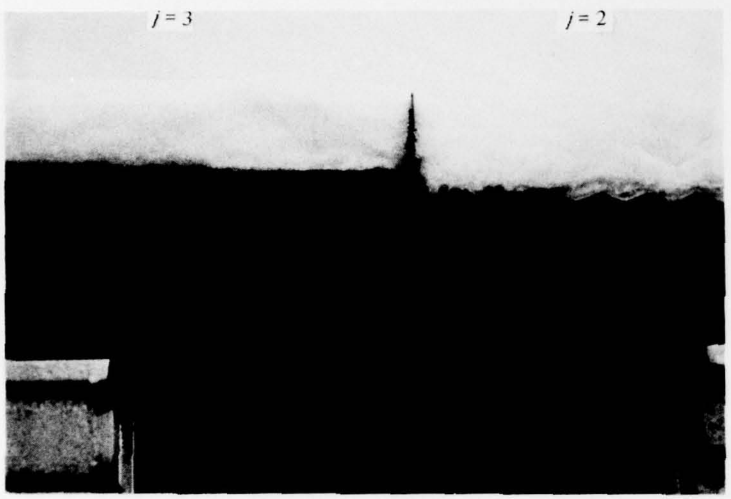
32 31

4b. 1400, 20 Dec 71.

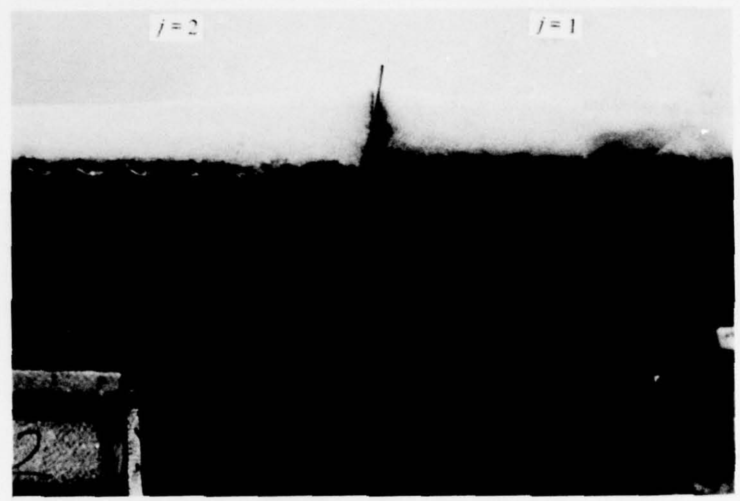
41



42



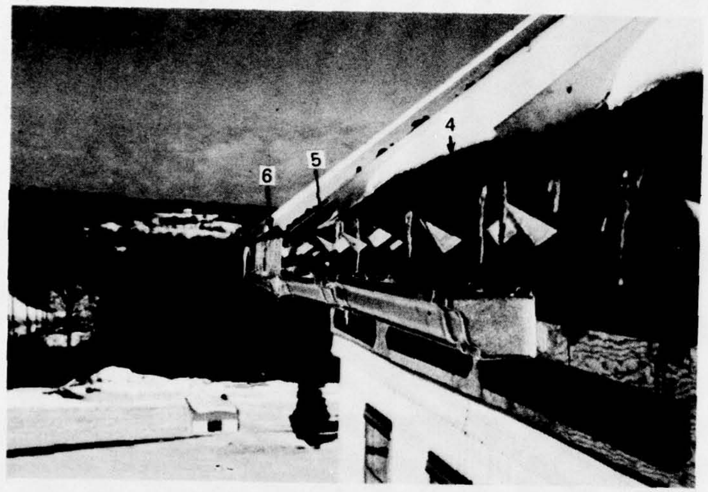
40



39

4c. 1430, 21 Dec 71.

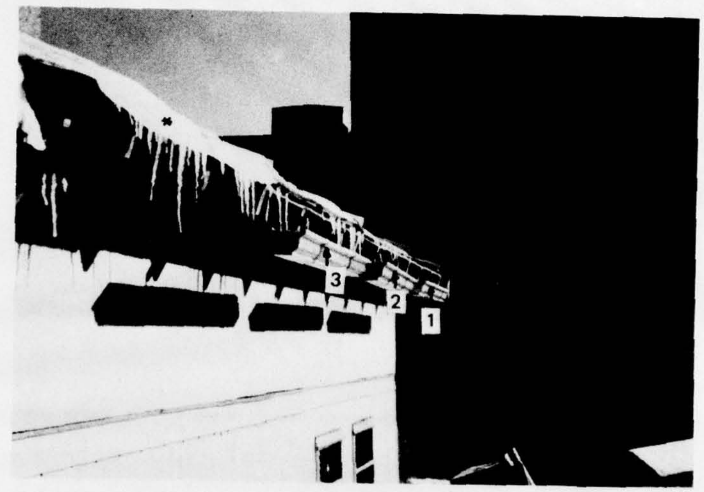
↓ From left to right j = 6, 5, 4



47

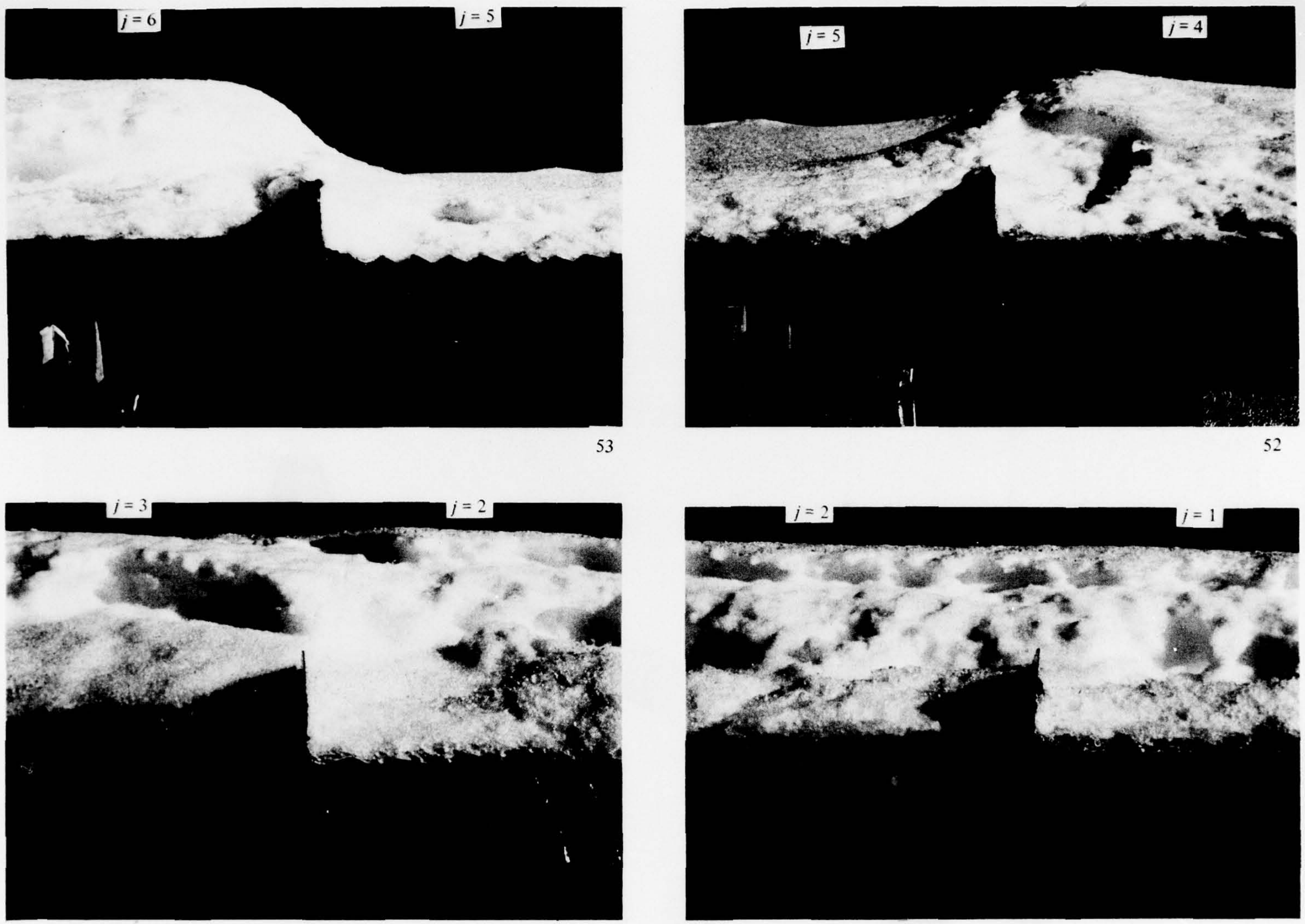
* Bare roof panel (not a test roof)

↓ From left to right j = 3, 2, 1



49

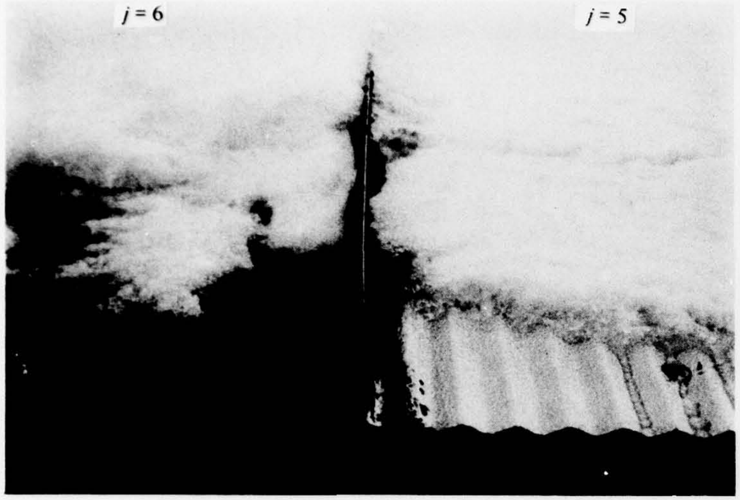
4d. 1000, 23 Dec 71.



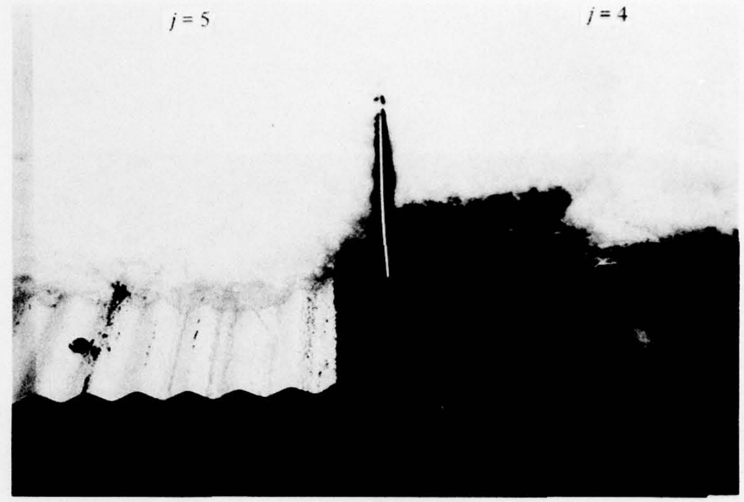
53 52

51 50

4e. 0830, 3 Jan 72.



67



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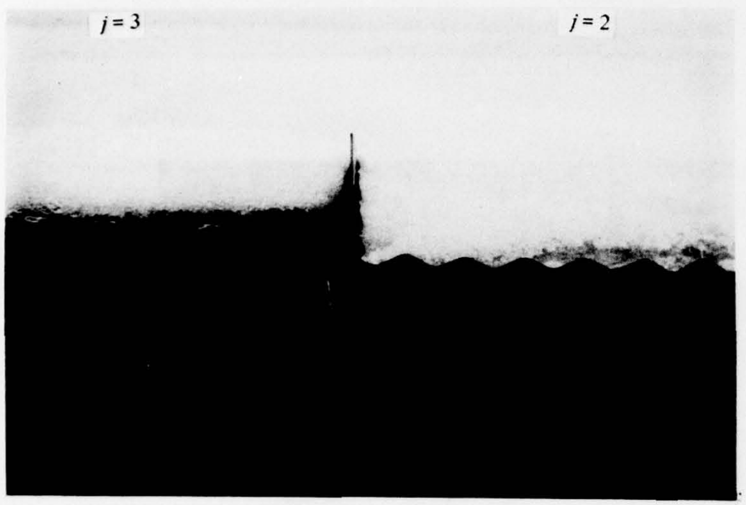

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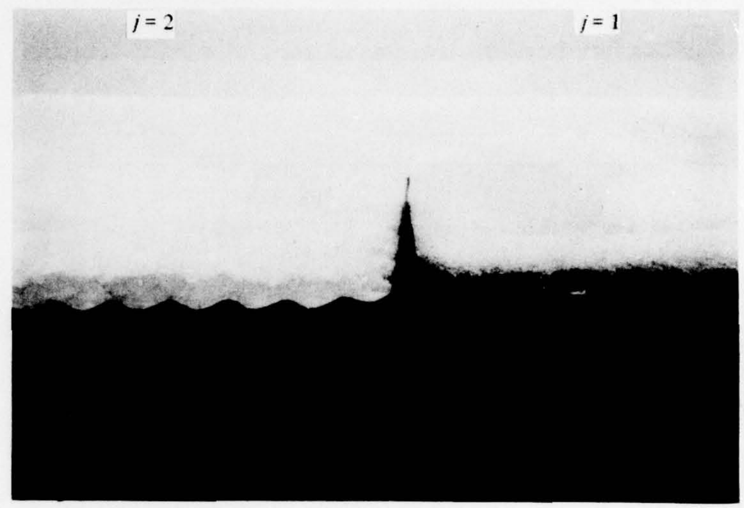
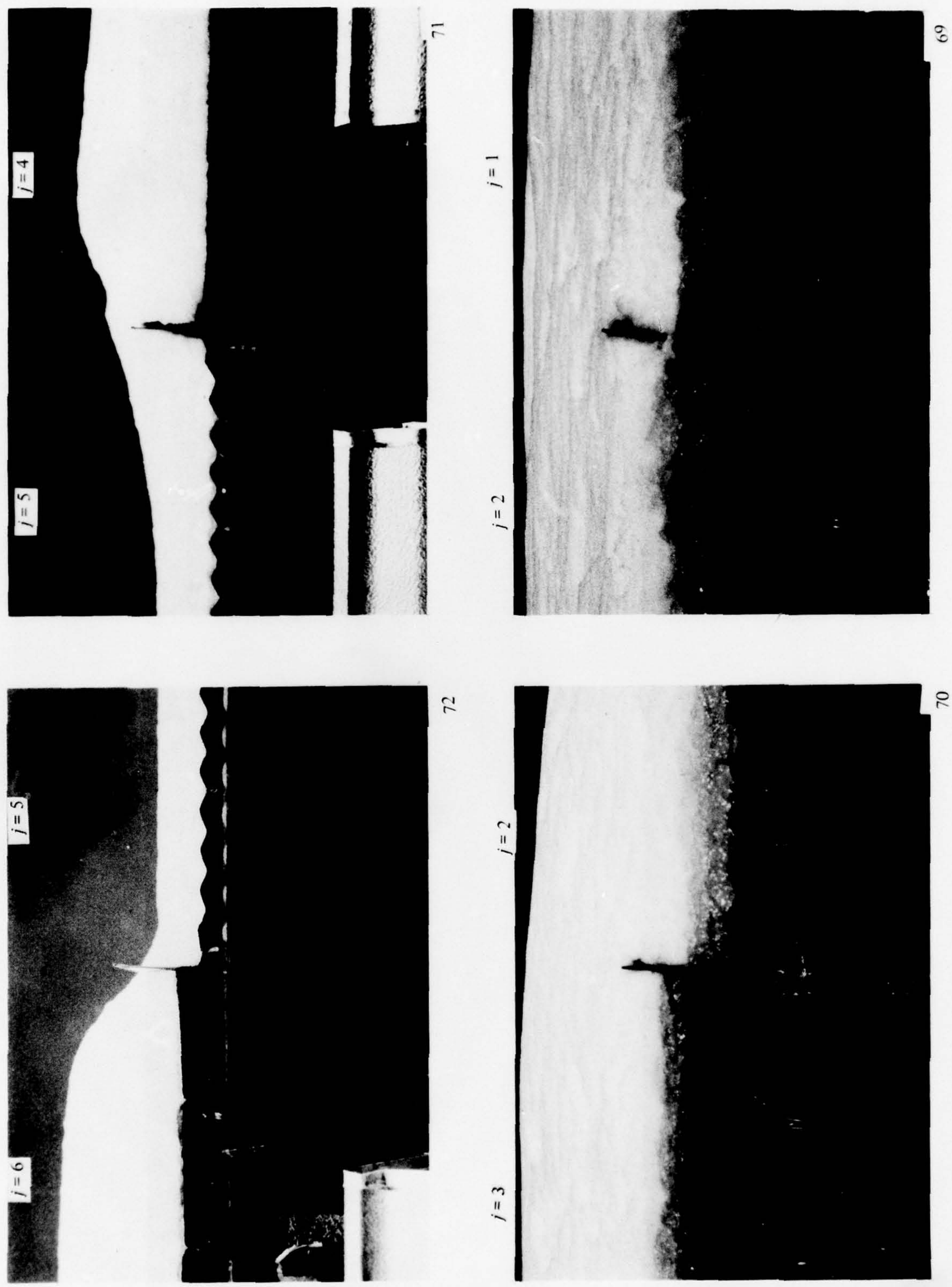
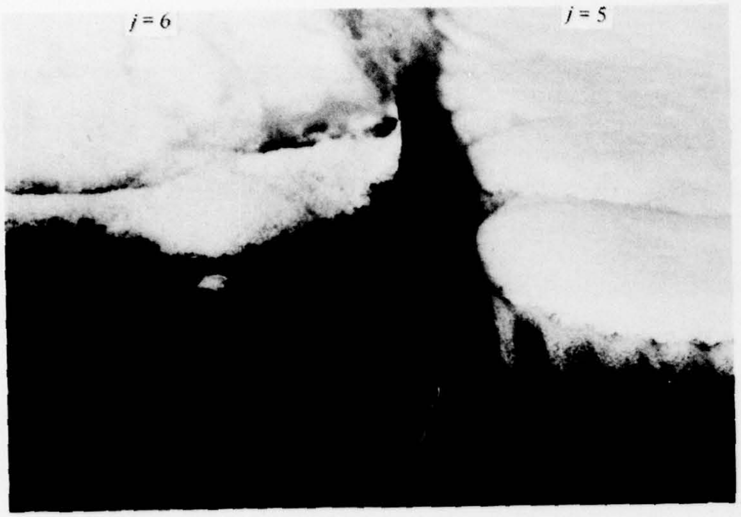


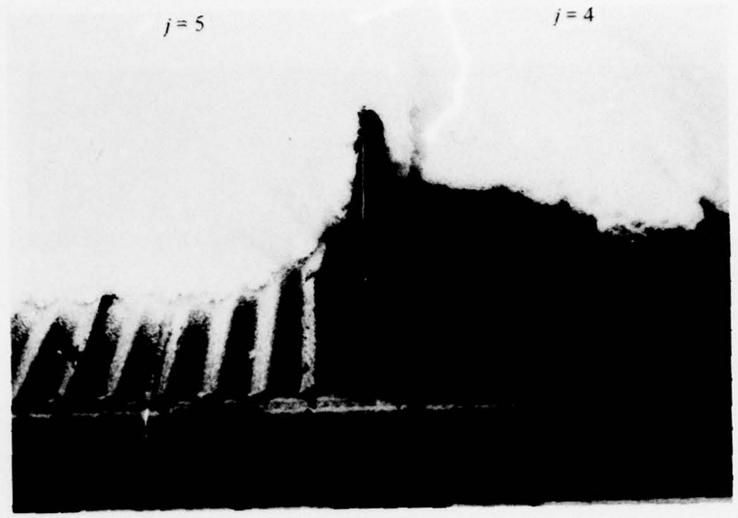
64

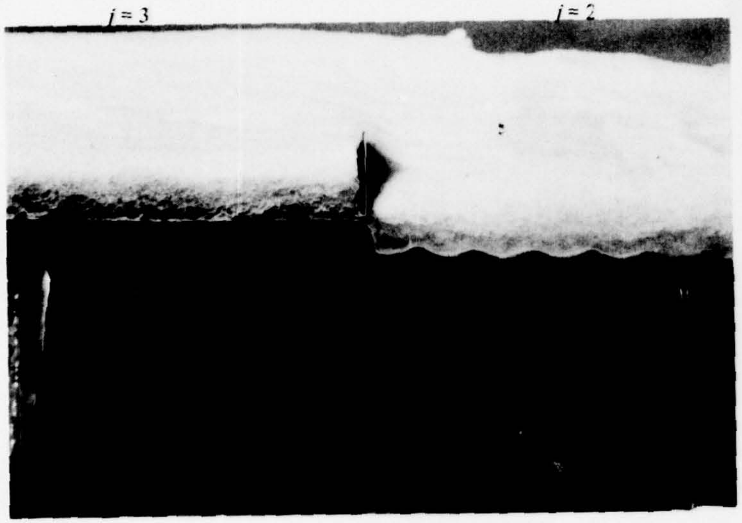
4f. 0830, 4 Jan 72.

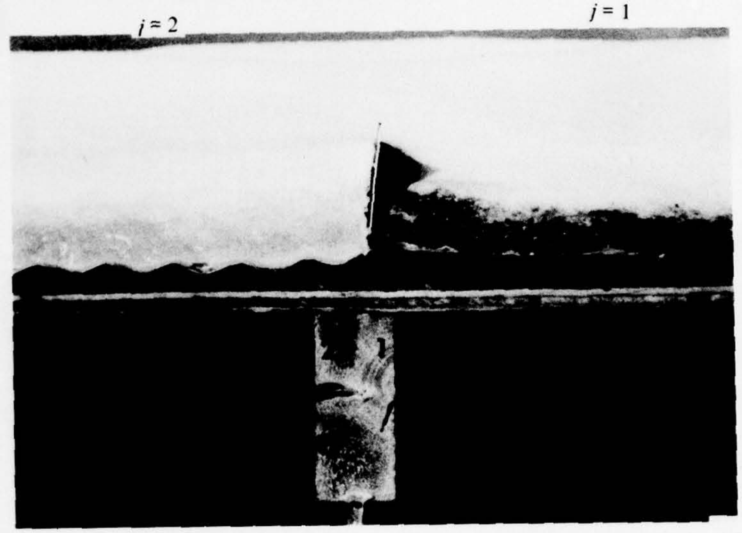


4g. 1245, 5 Jan 72.

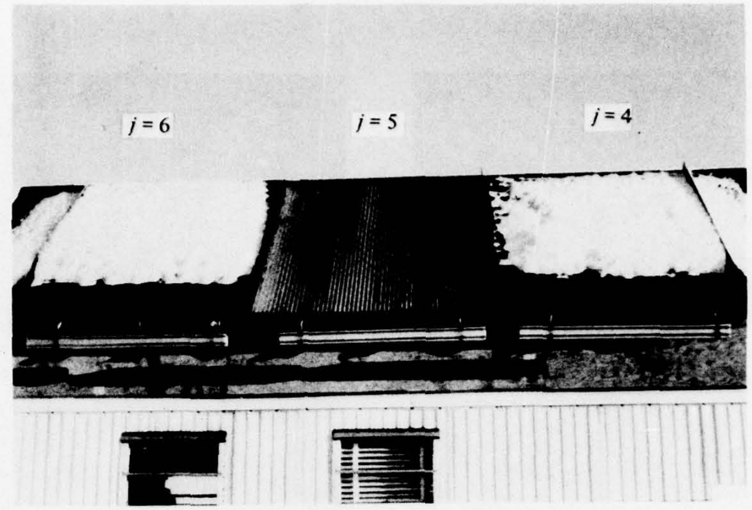


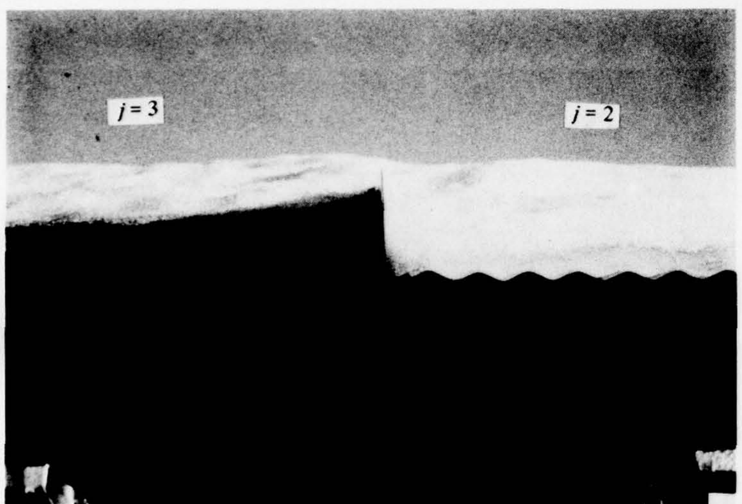




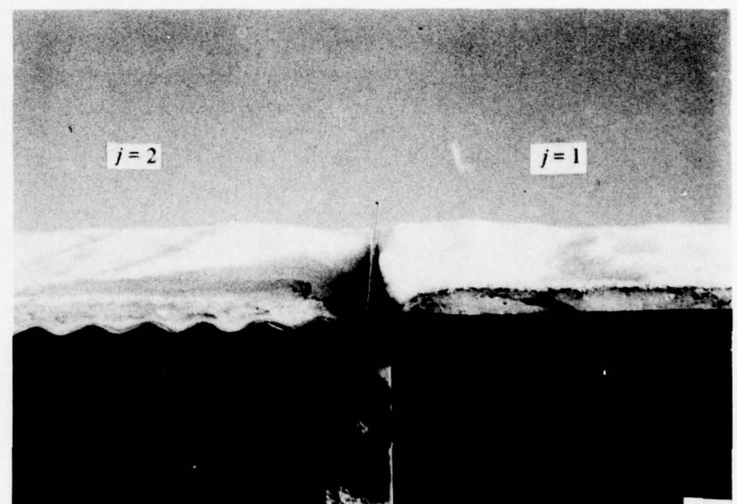


4h. 1500, 7 Jan 72.



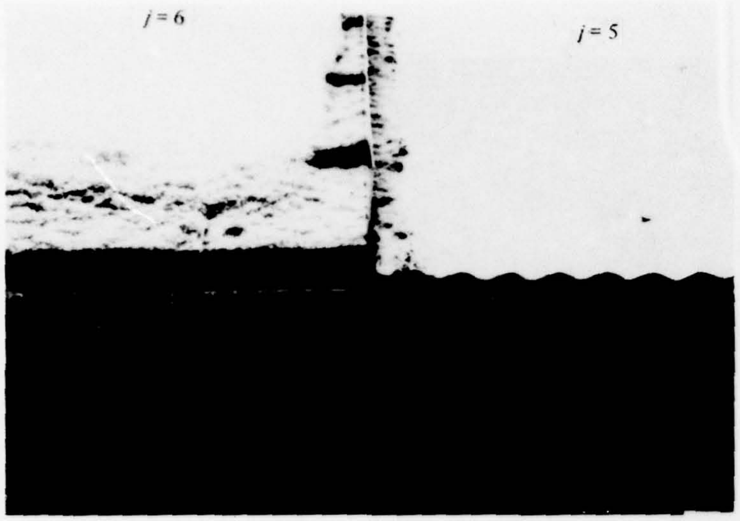


82

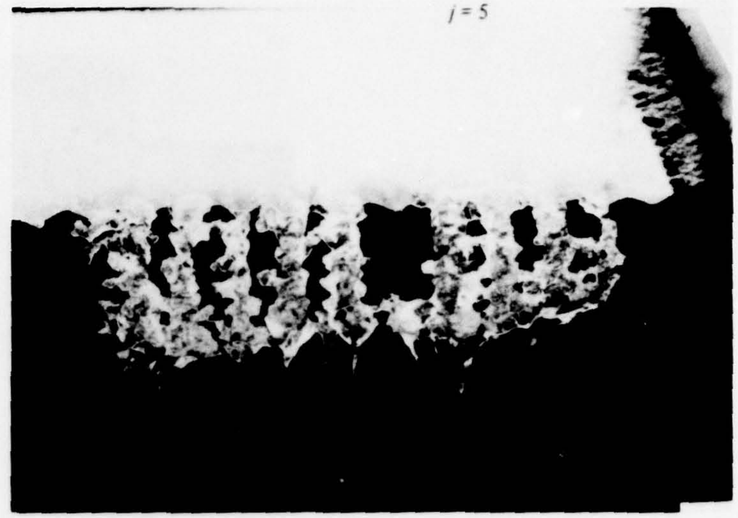


81

4i. 0800, 10 Jan 72.



104



102

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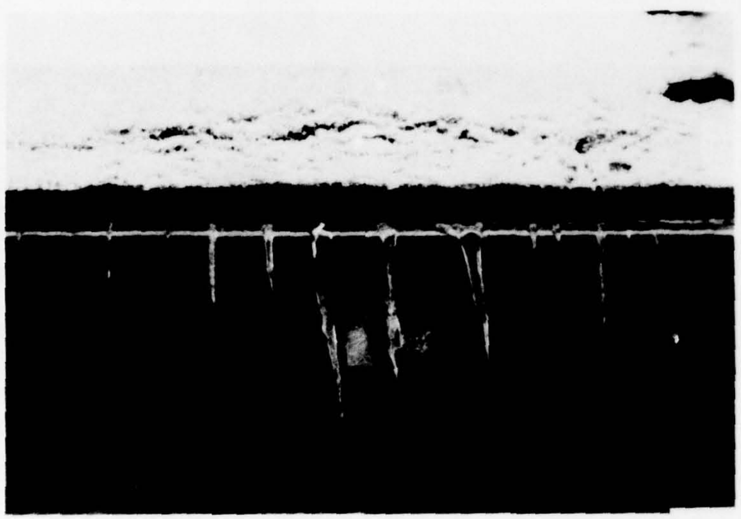
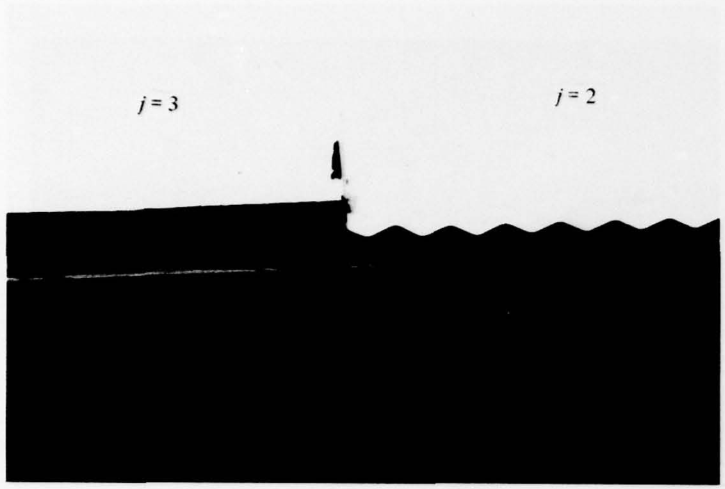


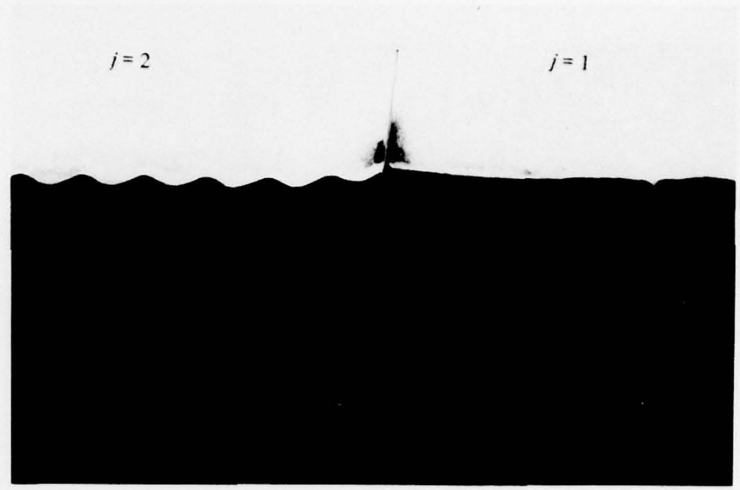
105

107

4j. 0815, 28 Feb 72.



98



96

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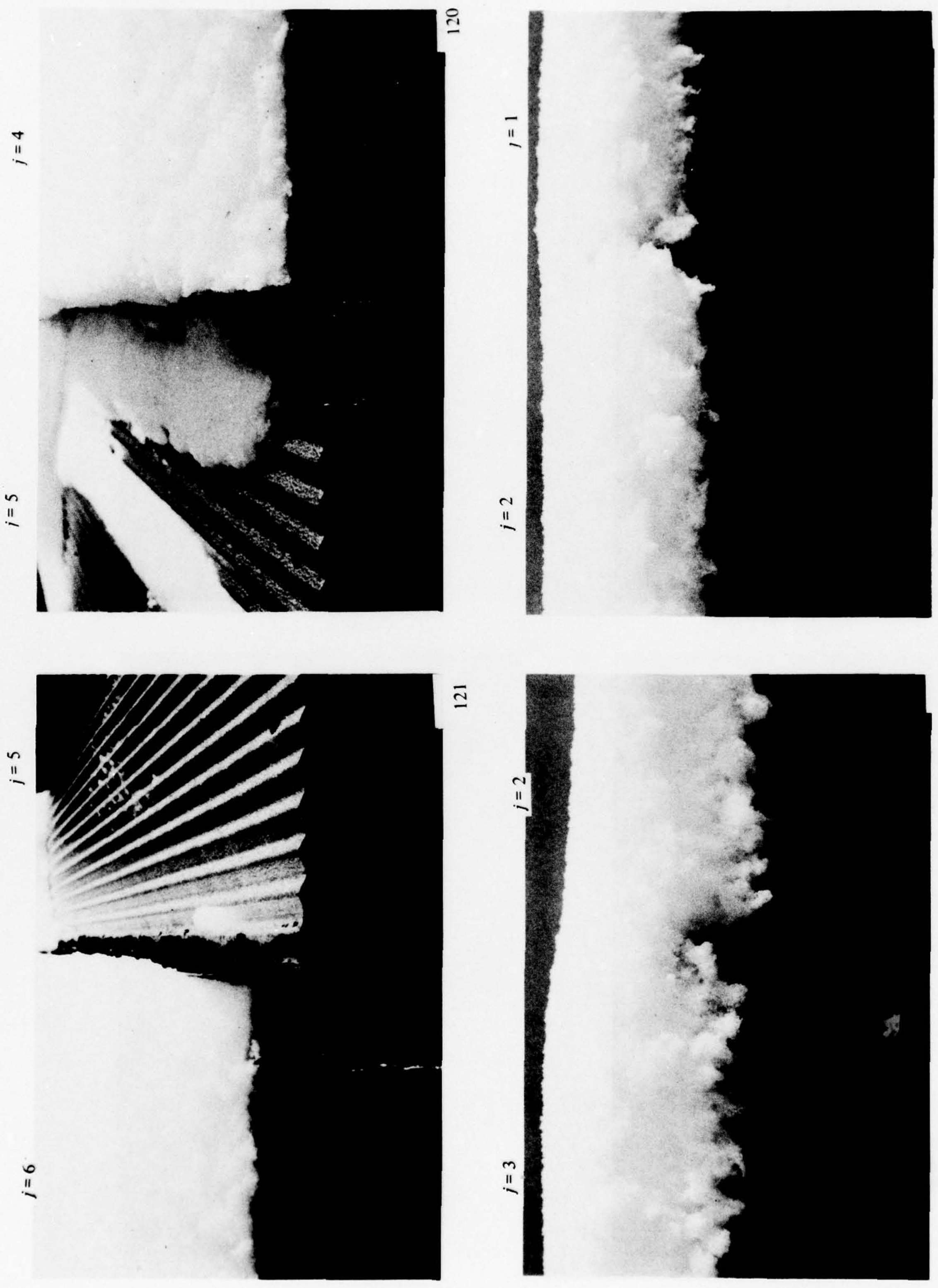
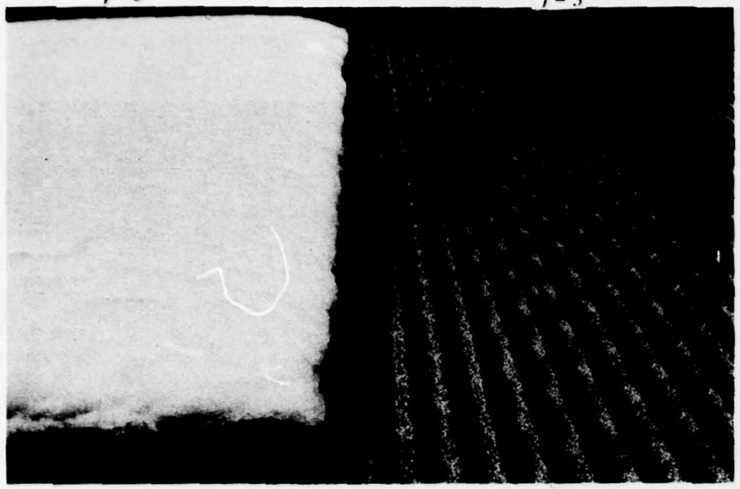
99

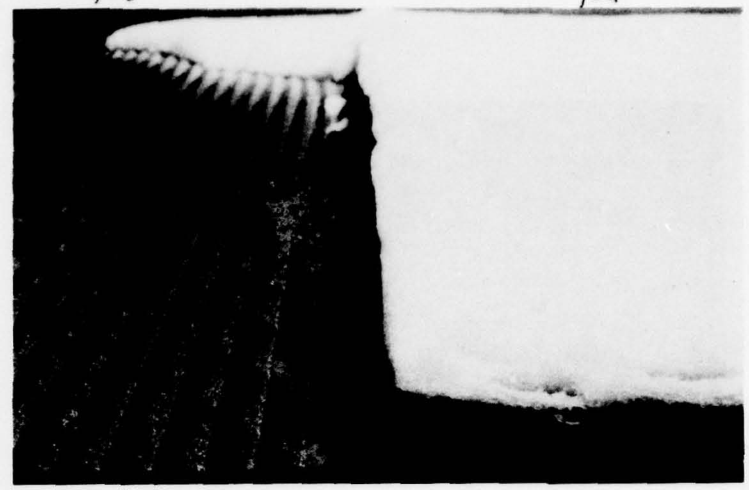
4k. 0815, 28 Feb 72.



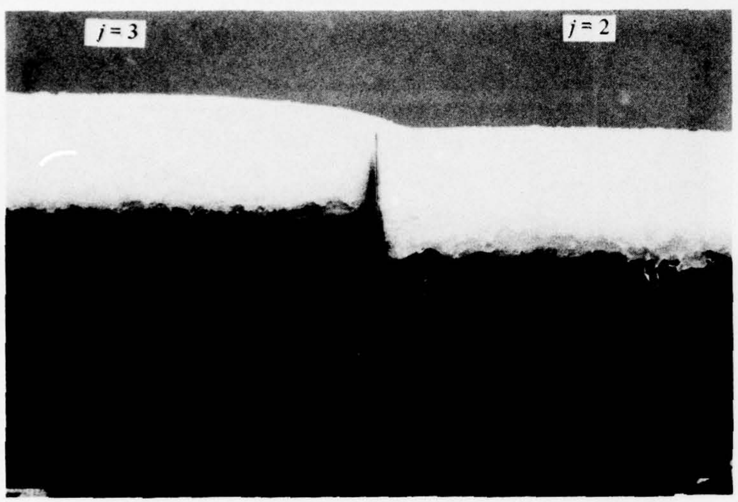
41. 0915, 16 Mar 72.



130



129



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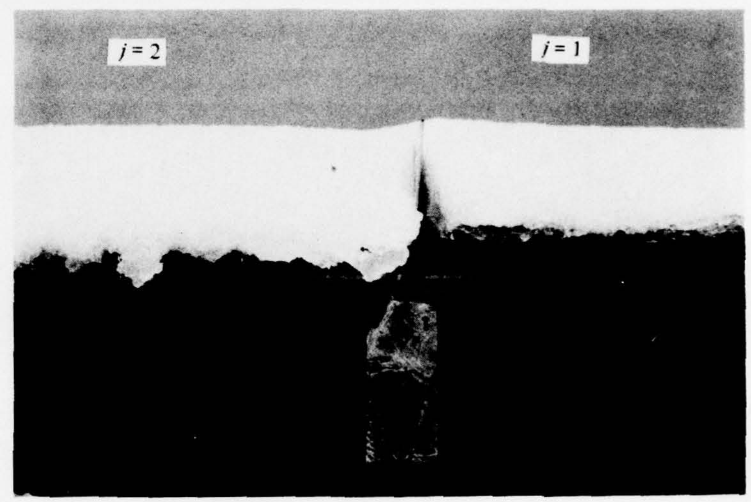


127

4m. 1115, 16 Mar 72.

Table XII. Heat accumulated by eaves and middle roof sections.

Data are for three daily time periods and two test days.

Date Time	Roof	Average temperature (°C) Eaves	Middle	Net heat flow (MJ/r^2) Eaves	Middle	Solar radiation (MJ/m^2)	Max. wind-speed (km/h)	Avg. air temp. (°C)
23 Dec 72 0000 to 0800	1	-1.11	+0.00	-0.028	-0.044	0	3.2	-5.7
	2	-0.555	"	+0.007	+0.133	"	"	"
	3	-1.94	+0.555	+0.001	+0.162	"	"	"
	4	-0.555	+0.00	+0.032	+0.141	"	"	"
	5	"	+0.555	-0.045	+0.162	"	"	"
	6	-0.83	+1.11	+0.019	+0.143	"	"	"
0800 to 1700	1	-0.555	+0.00	-0.019	+0.024	1.46	"	-3.55
	2	"	"	+0.126	+0.241	"	"	"
	3	-1.67	+0.555	-0.098	+0.2725	"	"	"
	4	-0.555	+0.00	+0.112	+0.190	"	"	"
	5	+0.00	+1.11	-0.018	+0.187	"	"	"
	6	-0.555	"	+0.101	+0.2225	"	"	"
1700 to 2400	1	"	-0.555	-0.024	-0.052	0	"	-3.3
	2	"	+0.00	+0.056	+0.148	"	"	"
	3	-1.11	+0.555	-0.265	+0.177	"	"	"
	4	-0.555	+0.00	+0.048	+0.151	"	"	"
	5	"	+1.11	-0.020	+0.178	"	"	"
	6	"	"	+0.049	+0.153	"	"	"
9 Jan 73 0000 to 0800	1	-26.67	-15.555	-0.158	+0.329	0	4.8	-26.9
	2	-23.33	-14.44	-0.425	+0.296	"	"	"
	3	-23.89	- 9.72	+0.087	+0.270	"	"	"
	4	-28.33	-16.67	-0.343	+0.287		"	"
	5	-25.555	-16.11	-0.149	-0.421	"	"	"
	6	-25.555	-16.67	-0.132	+0.165	"	"	"
0800 to 1700	1	- 2.22	-14.44	+0.972	+0.579	8.20	"	-16.9
	2	- 9.44	-13.33	+0.1885	+0.410	"	"	"
	3	-12.22	-11.11	+1.104	+0.605	"	"	"
	4	+ 1.67	-12.22	+0.476	+0.362	"	"	"
	5	- 3.89	- 8.89	+0.303	+0.208	"	"	"
	6	- 7.22	-13.89	+0.212	+0.5485	"	"	"
1700 to 2400	1	-17.78	-10.555	-0.240	+0.3225	0	"	-19.4
	2	-15.00	-10.00	-0.287	+0.316	"	"	"
	3	-11.67	- 6.94	+0.042	+0.418	"	"	"
	4	-21.11	- 9.44	-0.326	+0.133	"	"	"
	5	-18.33	-10.555	-0.196	-0.376	"	"	"
	6	-10.555	-10.28	-0.075	+0.077	"	"	"

Table XIII. Snow depths as a function of roof and original snow cover.

'Original snow cover' is the snowfall occurring in such close proximity in time as to be undissipated at the time of the first measurements of snow depth on the roofs following its cessation.

Original snowfall (cm)	Date snow depth measured	Time snow depth measured	Snow depths of jth roof (cm)					
			h_1	h_2	h_3	h_4	h_5	h_6
6.35	7 Dec 71 8 Dec 71	1045 0930	5.08 "	3.81 "	5.08 "	3.81 "	1.27 "	5.08 "
1.27	16 Dec 71 " "	0930 1130 1330	1.27 0.635 0	1.27 0.635 0	1.27 0.635 0	1.27 0 "	0 " "	1.27 0 "
7.62	18 Dec 71	1115	0	1.9 to 5.4	2.5 to 6.0	5.715	0	5.715
2.03	19 Dec 71	1300	"	0.6 to 3.5	1.9 to 5.7	4.13	"	3.175
6.86	21 Dec 71 " 22 Dec 71 23 Dec 71 "	0800 1430 0800 1000 1300	5.08 3.81 2.54 1.3 to 5.0 "	6.35 5.08 2.5 to 3.8 " "	7.62 " 3.8 to 7.6 " "	8.89 7.62 5.08 2.54 "	5.08 " " ? "	7.62 " 5.08 2.5 to 5.0 "
2.54	24 Dec 71 "	1010 1300	" 0	" 0	" 0	" 0	" 0	" 0
17.78	31 Dec 71	1030	16.51	20.32	20.32	16.51	?	17.78
7.62	3 Jan 72 4 Jan 72	0930 0800	17.145 15.24	19.685 17.78	19.685 15.24	13.97 8.89	5.08 2.54	19.685 16.51
2.79	5 Jan 72 10 Jan 72 "	1000 1300 1615	13.335 13.0 0	17.145 17.0 0	16.51 16.2 0	12.7 0 "	5.08 0 "	18.415 18.1 "
10.41	21 Jan 72	1830	2.54	4.44	4.44	6.35	6.985	5.08
2.54	24 Jan 72	1500	0	0	0	0	0	0
3.56	28 Jan 72	1500	2.54	2.54	2.54	2.54	2.54	2.54
5.84	4 Feb 72	?	0.5	0.5	3.5	3.5	0	0
0.76	7 Feb 72	"	0.6 to 2.5	0.6 to 2.5	0.6 to 2.5	0	"	"
40.39	28 Feb 72 29 Feb 72 1 Mar 72	0815 " "	5.715 5.6 0	6.35 6.2 0	10.16 10.0 0	2.54 0 "	2.54 0 "	3.81 0 "
6.35	6 Mar 72	0800	2.54	3.81	5.08	5.08	3.81	5.08
0.25	7 Mar 72	"	"	2.54	2.54	2.54	2.54	2.54
17.78	15 Mar 72 " 16 Mar 72 "	0830 1545 0800 1600	12.7 " 11.43 "	12.7 " " "	12.7 13.97 " "	12.7 13.97 12.7 0	trace 0 " "	12.7 14.605 13.97 0

Table XIII (cont'd).

Original snowfall cm	Date snow depth measured	Time snow depth measured	Snow depths of jth roof (cm) h_1	h_2	h_3	h_4	h_5	h_6
6.35	23 Dec 72	?	1.3	1.3	1.3	1.3	1.0	1.3
	24 Dec 72	"	"	"	"	"	"	"
	25 Dec 72	"	"	"	"	"	"	"
16.67	5 Jan 73	?	21.59	23.495	30.48	16.51	0	15.24
	8 Jan 73	"	"	"	"	15.24	"	"
	9 Jan 73	"	"	"	"	14.605	"	14.605
	10 Jan 73	"	"	"	"	13.97	"	"
	11 Jan 73	"	"	"	"	"	"	13.97
	12 Jan 73	"	"	"	"	12.7 to 14.0	"	"
	13 Jan 73	"	"	"	"	13.0	"	"
	14 Jan 73	"	"	"	"	"	"	"
	15 Jan 73	"	20.955	22.86	29.845	12.7	"	12.7
	16 Jan 73	"	20.32	"	"	10.16	"	"
	17 Jan 73	"	"	"	27.94	5.08	"	11.43
	18 Jan 73	"	5.08	7.62	15.24	0	"	2.54
	19 Jan 73	1315	2.03	2.54	5.08	"	"	0
	22 Jan 73	?	0	0	0	"	"	"
29.46	29 Jan 73	1240	20.32	20.32	20.32	25.4	12.7	17.78
	16 Feb 73	?	2.54	2.54	2.54	2.54	2.54	2.54

the aluminum roofs that are the exception. The reason for this is that the no. 5 (high-slope, aluminum) roof was the roof with the least snow cover and therefore most able to interact strongly with solar radiation. Again, a study of Table II reveals that τ' is least for the aluminum roofs and therefore, geometrically speaking, these roofs had the least ability to hold snow cover.

Comparison of the two types of stability rankings is interesting. While the no. 3 (low-slope, cedar) roof had the most tendency to maintain the same temperature profile, when changes did occur, they were more drastic changes than those that occurred for the no. 4 (high-slope, asphalt) roof. The implication is that the cedar roofs changed profile less often but more drastically than the asphalt roofs and that the aluminum roofs changed both more often and more drastically than roofs of either asphalt or cedar composition. This result can be understood by referring to Table II and noting that the thermal conductivity k' and thermal diffusivity A' are similar for asphalt and cedar but differ by orders of magnitude for aluminum compared to either asphalt or cedar.

The next question of interest is when did the profiles change and what relationships did the changes have to solar radiation? Refer to Table VI. The temperature profiles of all the roofs were most stable during the seven hours before dawn and became a complex function of the interaction between solar radiation, roof characteristics, and snow cover during the ten hours from dawn to dusk. They then tended to return to their predawn status in the seven hours after dusk. In general, each roof tended to have one characteristic profile in the absence of solar radiation and another or a series of other profiles in the presence of solar radiation. The ridge, eaves, and low sections heated most rapidly while the middle, under-deck, and floor sections responded most slowly. The no. 5 (high-slope, aluminum) roof, as expected from the results given above, provided the most extreme example of a characteristic profile change. When solar radiation was applied, the temperature profile essentially reversed itself so that the cooler sections in the early morning became the warmer sections at noon.

Using Table VI and ordering according to the tendency to exhibit this type of profile change:

no. 5 (high-slope, aluminum) roof
no. 4 (high-slope, asphalt) roof
no. 3 (low-slope, cedar) roof
no. 2 (low-slope, aluminum) roof
no. 6 (high-slope, cedar) roof
no. 1 (low-slope, asphalt) roof

Except for the no. 3 (low-slope, cedar) roof, this order implies that the controlling factors are k' and slope. For each composition, the high slope is more prone to

Table XIV. Snow coverage as a function of roof and original snow cover.

"Original snow cover" is the snowfall occurring in such close proximity in time as to be undissipated at the time of the first measurements of snow coverage on the roofs following its cessation.

Original snowfall (cm)	Date coverage measured	Time coverage measured	SNOW COVERAGES OF jth ROOF (%)					
			Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
6.35	7 Dec 71	1045	100	100	100	100	100	100
	8 Dec 71	0930	87.5	87.5	87.5	87.5	87.5	87.5
1.27	16 Dec 71	0930	"	"	"	"	0	"
	"	1130	"	"	"	0	"	0
	"	1330	0	0	0	"	"	"
7.62	18 Dec 71	1115	0	100	100	100	0	100
2.03	19 Dec 71	1300	"	87.5	98	96	"	98
6.86	21 Dec 71	0800	100	100	100	100	40	100
	"	1430	"	"	"	"	"	"
	22 Dec 71	0800	"	"	"	"	33	"
	23 Dec 71	1000	"	"	"	87.5	27	90
	"	1300	"	"	"	"	"	"
2.54	24 Dec 71	1010	25	75	75	"	0	"
	"	1300	0	0	0	0	"	0
17.78	31 Dec 71	1030	100	100	100	100	25	100
7.62	3 Jan 72	0930	"	"	"	97	97	97
	4 Jan 72	0800	97	97	97	87	87	87
2.79	5 Jan 72	1000	100	100	100	100	100	100
	10 Jan 72	1300	30	30	30	0	0	trace
	"	1615	0	0	0	1	"	0
10.41	21 Jan 72	0830	100	100	100	100	33	100
2.54	24 Jan 72	1500	0	trace	trace	0	0	0
3.56	28 Jan 72	1500	100	100	100	trace	100	100
5.84	4 Feb 72	?	"	"	"	0	0	?
0.76	7 Feb 72	?	?	?	?	"	"	0
40.39	28 Feb 72	0815	97.9	97.9	99	94.8	15	97.9
	29 Feb 72	0800	99	87	95	0	0	0
	1 Mar 72	"	0	0	0	"	"	"
6.35	6 Mar 72	"	100	100	100	100	100	100
0.25	7 Mar 72	0800	100	100	100	100	100	100
17.78	15 Mar 72	0830	"	"	"	"	trace	"
	"	1545	"	"	"	"	0	"
	16 Mar 72	0800	"	"	"	"	5	"
	"	1600	77	75	80	0	0	0
16.76	23 Dec 72	?	100	100	100	100	100	100
	24 Dec 72	"	"	"	"	"	"	"
	25 Dec 72	"	"	"	"	"	"	"
6.35	5 Jan 73	"	90	90	90	75	30	75
	8 Jan 73	"	"	"	"	"	"	"
	9 Jan 73	"	"	"	"	"	"	"

Table XIV (cont'd).

Original snowfall (cm)	Date coverage measured	Time coverage measured	SNOW COVERAGES OF jth ROOF (%)					
			γ_1	γ_2	γ_3	γ_4	γ_5	γ_6
	10 Jan 73	"	"	"	"	"	"	"
	11 Jan 73	"	87	87	87	40	20	"
	12 Jan 73	"	"	"	"	"	"	"
	13 Jan 73	"	"	"	"	"	"	"
	14 Jan 73	"	"	"	"	"	"	"
	15 Jan 73	"	"	"	"	"	"	"
	16 Jan 73	"	"	"	"	33	0	67
	17 Jan 73	"	75	75	75	30	"	60
	18 Jan 73	"	67	67	67	0	"	17
	19 Jan 73	1315	60	30	17	"	"	0
	22 Jan 73	?	0	0	0	"	"	"
29.46	29 Jan 73	1240	100	100	100	100	75	100
	16 Feb 73	?	"	"	"	"	70	"

exhibit the characteristic profile reversal (except for the cedar roofs). For each slope, the compositions in order of tendency to exhibit profile reversal are aluminum, asphalt, and cedar [except for the no. 3 (low-slope, cedar) roof]. The latter order is precisely the order of decreasing values of k'.

Why does the no. 3 (low-slope, cedar) roof appear as an exception? Examination of Table VI reveals that, unlike the case for the other roofs where it is the ridge and eaves sections that are responding, in the case of the no. 3 (low-slope, cedar) roof, it is the floor and ridge sections that are responding most rapidly. It has already been noted that this roof retained too much snow cover to offer a true response to solar radiation. However, it appears that faulty insulation in the floor allowed heat from inside the building to affect the profile of the roof. As there were only two measurements of floor temperature, rather than one for each roof, it may be concluded that the no. 3 (low-slope, cedar) roof actually was the least likely to exhibit profile reversal due to solar radiation and, just because of its failure to react to solar radiation, it showed the weaker effects of heat loss from the interior of the building. In other words, the snow cover on top of the roof insulated it from solar radiation more effectively than the floor insulation from interior heat, which, like solar radiation, was applied only during daylight hours.

Common discussions in the literature[2] tend to lay the major blame for heating of the middle section of a roof on warm attic air and to discount the influence of solar radiation. It is clear from the results here that the true situation is not so simple. Warm attic air and solar radiation affect every roof and it is the slope, roof geometry, and thermal conductivity of its covering that determine which effect is greatest. In particular, for a roof of high slope covered with a material of high thermal conductivity, it is solar radiation rather than warm attic air that dictates the final temperature profile. Furthermore, the same is probably true of any roof that does not consistently retain a snow cover approaching 30 cm in depth.

What causes the observed profile reversal? The ridge section responses are understandable, since the ridge is the section most exposed to solar radiation and warm attic air. How is it that the eaves section heats more rapidly than the middle section? This may be evidence that the eaves are heated from below by warm air convection upwards on the wall and collecting under the eaves. The higher the slope, the greater the ability of the roof to retain warm air under the eaves and the greater the thermal conductivity of the roof composition, the more rapidly it would heat. This collection of warm air under the eaves has been observed in thermograms; Figure 5 provides an example.[7]

Comparative temperatures of roofs by section – rankings

The temperature rankings compare the roof temperatures for a specific section. These data are summarized in Tables VII to X.

As for the discussion of the profiles above, we begin with the question of simple stability. For which section are the roof temperatures most nearly all in the same relationship? From Table VII, the answer in order of decreasing stability is:

floor
middle
under deck
ridge
low
eaves

Figure 5. Thermograph of eave section showing trapped heat under eave. (Ref. 7, Fig. 9.)

The results for the floor section are skewed somewhat because of the fact that there were only two temperature measurements rather than one for each roof. The implication is then that the middle section is the section most characteristic of the roof as a whole.

Moving to Table VIII, the question changes to what section's rankings change the least in terms of significant changes? The order becomes:

floor
middle
under deck
low
eaves
ridge

This result could have been expected, since it was the ridge, low, and eaves sections that were found above to respond most rapidly to the application of solar radiation.

When do the changes in temperature rankings occur for a given section? The answer is in Table IX. The middle section's ranking remains nearly the same throughout the day. At the other extreme, the eaves section's ranking changes continually with changes in the meteorological variables and tends to reverse itself; the roofs that are warmest at night tend to become the coolest roofs during daylight. In order of the tendency to show this ranking reversal with solar cycle:

eaves
low
ridge
under deck
floor
middle.

If the middle section is the section most characteristic of the roof as a whole, its characteristic ranking is the one that most nearly answers the question of which roof tends to be coolest and which tends to be warmest. The maximum ranking for the middle section is (421)365. This means that the no. 1 (low-slope, asphalt), no. 2 (low-slope, aluminum), and no. 4 (high-slope, asphalt) roofs tend to respond alike and to be the coolest roofs, while in order of increasing temperature, the remaining roofs are:

no. 3 (low-slope, cedar) roof
no. 6 (high-slope, cedar) roof
no. 5 (high-slope, aluminum) roof.

This implies that the higher the slope, the greater the solar heating of the middle section. The fact that the middle section tends to be cooler for the two asphalt roofs (regardless of slope) implies that a secondary effect due to composition is involved. This compositional effect may be due to thermal diffusivity since this property increases in the order asphalt, cedar, aluminum like the observed temperature ranking. That is, the thermal diffusivity of aluminum is orders of magnitude greater than the thermal diffusivity of the other two materials and it is the aluminum roofs that are most different from each other, and it is the asphalt roofs that are the most similar.

The effects of warm attic air may be determined by studying the rankings for the under deck and floor sections. Table VIII clearly reveals that slope is the dominant effect and that the lower the slope, the warmer the attic air. Subsidiary compositional effects are that the attic air tends to be cooler under an aluminum roof than under a cedar roof but that the slope does not affect the attic air temperature of an asphalt roof as much as it does roofs of the other two materials. While the no. 1 (low-slope, asphalt) roof has the warmest attic air of the low-slope roofs, the no. 4 (high-slope, asphalt) roof has the coolest attic air of

Table XV. Meltwater volume collected subsequent to each snowfall.

Expressed as a volume and as a fraction of the original mass of snow cover on the roof immediately after the snowfall's cessation. Dates given are those from cessation of the snowfall to dissipation of snow cover on all roofs or the beginning of a new snowfall, whichever was applicable.

Snowfall dates	Original snowfall (cm)	Meltwater fraction and meltwater volume for jth roof ($\times 10^{-3}$ m^3)						Average total solar radiation (MJ/m^2)
		V_1	V_2	V_3	V_4	V_5	V_6	
7 Dec 71 to 15 Dec 71	6.35	0.74 33.50	0.76 25.96	0.49 22.38	0.55 18.57	0.78 8.85	0.66 29.72	1.48
16 Dec 71 to 17 Dec 71	1.27	1.81* 17.98	1.955* 19.38	2.20* 21.77	1.245* 12.34	0	0.07 0.71	3.55
18 Dec 71	7.62	0	0	0	0	0	0	2.075
19 Dec 71 to 20 Dec 71	2.03	0	0	0	0	0	0	3.1
21 Dec 71 to 23 Dec 71	6.86	0.045 2.07	0.05 2.84	0.01 0.62	0.04 3.37	0.31 5.67	0.01 0.55	2.60
24 Dec 71	2.54	0	0.18 3.86	0.09 3.41	0	0	0.065 1.97	0.35
31 Dec 71 to 2 Jan 72	17.78	0	0	0	0	0	0	2.61
3 Jan 72 to 4 Jan 72	7.62	0.02 3.78	0.05 9.46	0.005 0.95	0.05 6.63	0.13 5.67	0.02 2.84	2.04
5 Jan 72 to 10 Jan 72	2.79	0.25 29.33	0.25 39.08	0.24 35.49	0.40 45.66	0.33 15.14	0.36 59.16	3.65
21 Jan 72 to 23 Jan 72	10.41	0.15 3.31	0.14 5.67	0.01 0.47	0.27 15.14	0.12 2.48	0.35 15.85	3.98
24 Jan 72	2.54	0	0	0	0	0	0	2.48
28 Jan 72 to 3 Feb 72	3.56	0	0	0	0	0	0	2.54
4 Feb 72 to 6 Feb 72	5.84	0	0	0	0	0	0	?
7 Feb 72	0.76	0	0	0	0	0	0	?
28 Feb 72 to 1 Mar 72	40.39	0.57 28.40	0.61 34.07	0.16 14.19	1.41* 30.28	2.78 9.46	1.22* 40.70	8.22
6 Mar 72	6.35	0	0.03 0.95	0	0.15 6.62	0.14 4.73	0	?
7 Mar 72 to 14 Mar 72	0.25	0	0	0	0	0	0	?
15 Mar 72 to 16 Mar 72	17.78	0.26 29.33	0.27 30.28	0.22 24.6	0.375 42.58	0	0.375 42.58	9.37

***Cases where it exceeds unity were caused by accumulations of ice from prior snowfalls melting and contributing to the meltwater volume of the snowfall in question.**

Table XVI. Degree of icing.

Using the semi-quantitative definition of "degree of icing," visual inspection was used to estimate the relative icing on the test roofs. The visual data are recorded photographically in Figure 4. Refer to Table I for the definition of *I*.

Observation date	Degree of icing on each test roof I_1	I_2	I_3	I_4	I_5	I_6	Figure 4 photo nos.
7 Dec 71	0	0.75	0	0	0	0	15, 17, 19, 22
20 Dec 71	0	0	0	0	0	0.25	31, 32, 34, 36
21 Dec 71	0	1.00	0	0	0	0	39, 40, 41, 42
23 Dec 71	0.50	0.50	0.50	0.25	0.25	0.25	47, 49
3 Jan 72	0	0.50	0	0	0	0	50, 51, 52, 53
4 Jan 72	0	1.00	0.75	0.25	0.50	0.25	64, 65, 66, 67
5 Jan 72	1.00	1.00	1.00	0	0.50	0.50	69, 70, 71, 72
7 Jan 72	0	1.00	0.25	0	0.25	0	75, 77, 78, 79
10 Jan 72	1.00	1.00	1.00	0	0	0	81, 82, 84
28 Feb 72	0.50	0.50	0.50	0.25	0.50	0.50	96, 98, 99, 102, 104, 105, 107
16 Mar 72	0	0	0	0	0.25	0.25	118, 119, 120,121
"	0.75	0.75	0.75	0	0	0	127, 128, 129,130

the high-slope roofs and, in fact, is more like its low-slope counterpart than the other high-slope roofs.

Since the middle section's maximum ranking is not at all similar to the under-deck section's maximum ranking, (421)365 as compared with 564123, respectively, it is clear that solar radiation rather than warm attic air had the most effect on the roofs as a whole.

What effect is dominant in producing the ranking reversals? Compositional effects must be separated from slope effects. Refer to Tables X and XI. In Table X, all of the possible equal temperature cases are listed. Study of the percentage of the total test hours for which each case was observed for each section (exclusive of the floor section) reveals:

1) Only the middle and low sections exhibited any of the possible equal temperature cases for more than 50% of the test hours.

2) The equalities (41) and (21) were the only equalities observed for more than 50% of the test hours.

3) For all sections, either (41) or (21) was the equality most often observed.

These results agree with previous indications that, for asphalt, compositional effects are dominant and, for aluminum and cedar, slope and geometrical effects are dominant. Table XI shows the data analyzed from the opposite point of view and shows the percentage of test hours for which a definitive slope dependence was observed. This analysis implies:

1) Attic air temperature increases with slope.

2) Ridge temperature decreases with slope.

3) Middle and low sections increase in temperature with slope but do not respond to a change in slope as readily as the ridge, under-deck, and floor sections.

4) The eaves section shows a stronger dependence upon composition than on slope.

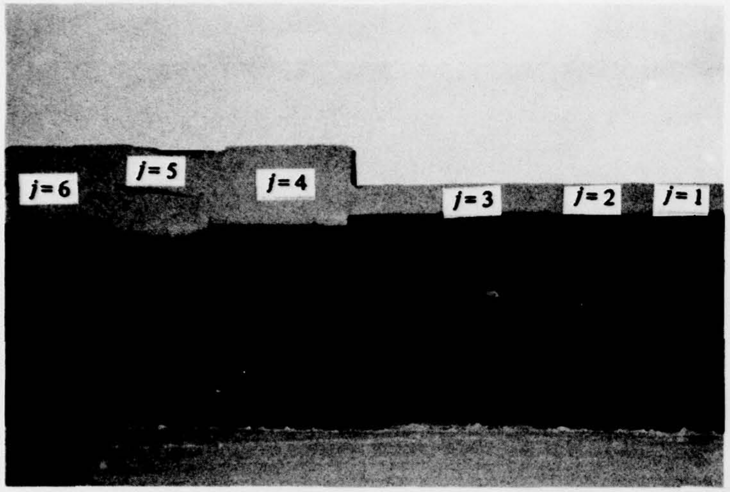
Heat flow and accumulation

For the two test days that were compared, one had much less solar radiation than the other. In addition, for the test day with the most solar radiation, the snow cover was deepest but least uniform, with the no. 5 (high-slope, aluminum) roof being bare and the eaves of the other roofs exposed. For the day of least solar radiation, the snow cover was thin but uniform and all sections of every roof were covered. (Refer to Table XII.)

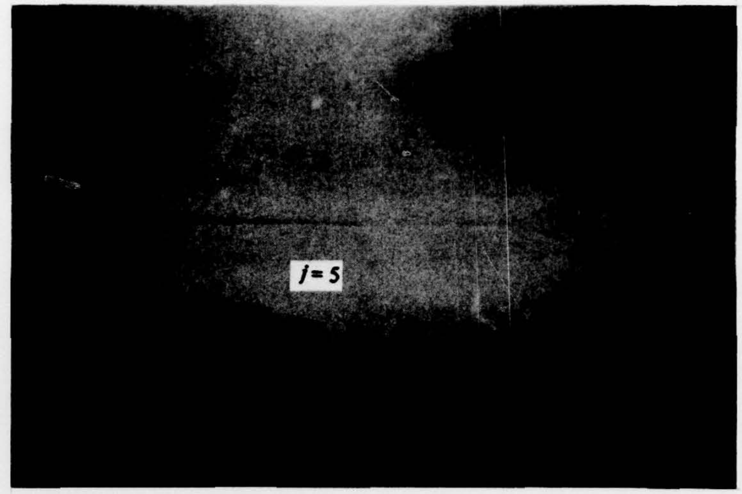
For the day with low solar radiation, the heat balance of all the roofs for both the middle and eave sections did not change significantly throughout the solar cycle. The no. 1 (low-slope, asphalt) and no. 5 (high-slope, aluminum) roofs tended to lose heat and the no. 2 (low-slope, aluminum), no. 4 (high-slope asphalt), and no. 6 (high-slope, cedar) roofs tended to gain heat throughout the day for the eaves section. For the middle section, all roofs except no. 1 (low-slope, asphalt) tended to gain heat during the daylight.

For the day with high solar radiation, the heat balance changed markedly for the eave section (exhibiting an increase in heat accumulation for all roofs) on all roofs but did not change much for the middle section except in the case of the no. 5 (high-slope, aluminum) roof. For the no. 5 (high-slope, aluminum) roof,

0815 29 Dec 72

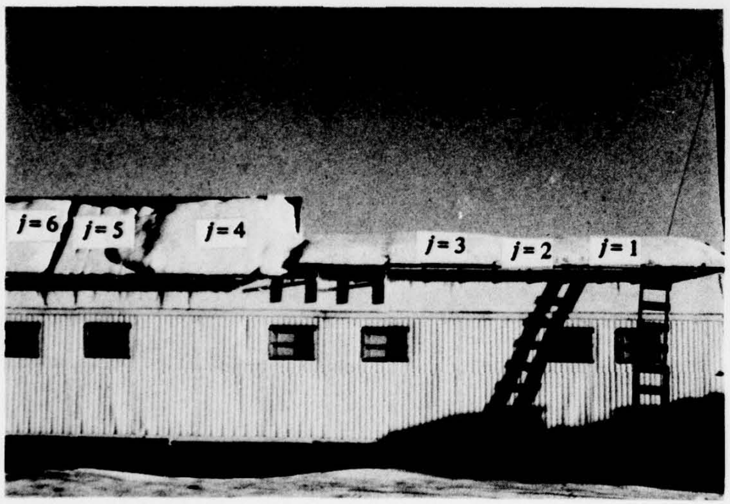


149

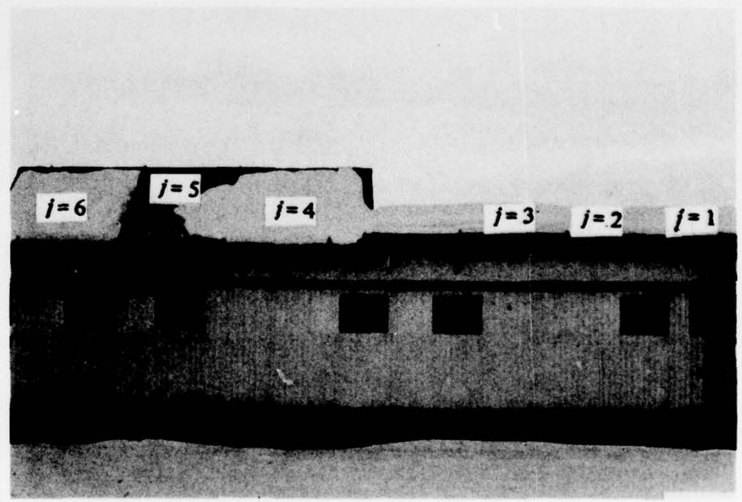


150

0930 3 Jan 73



1600 3 Jan 73



152

Figure 6a.

Figure 6. Change in coverage of roofs with time.

1430 5 Jan 73

1600 8 Jan 73

1335 10 Jan 73

1600 15 Jan 73

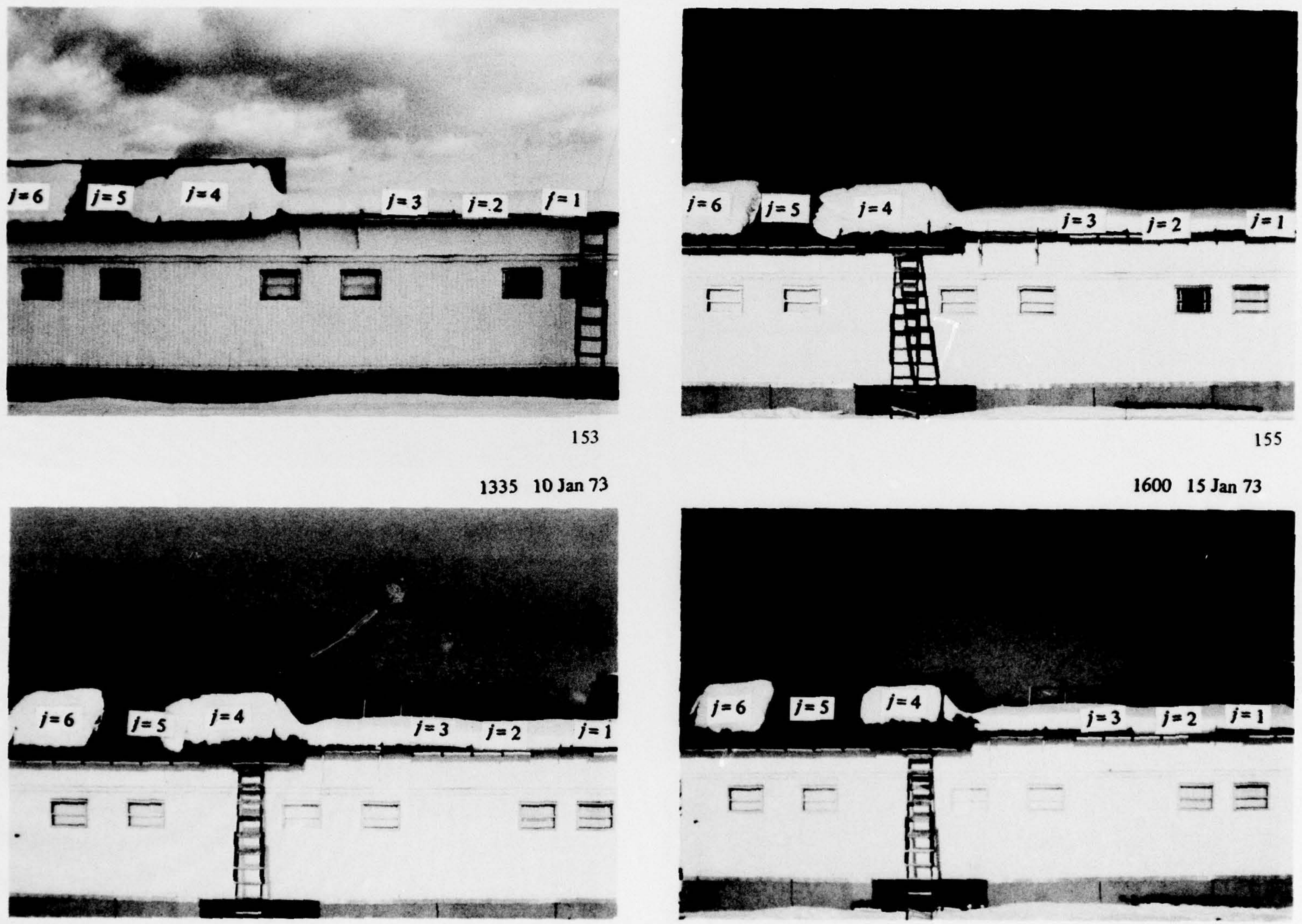
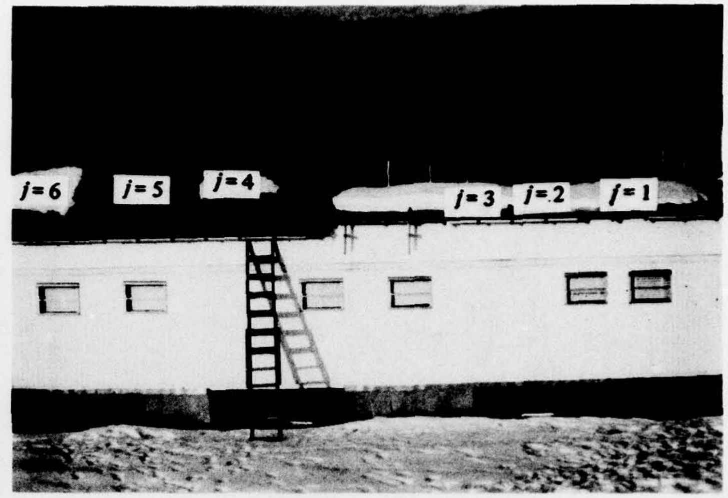


Figure 6b.

1625 · 16 Jan 73

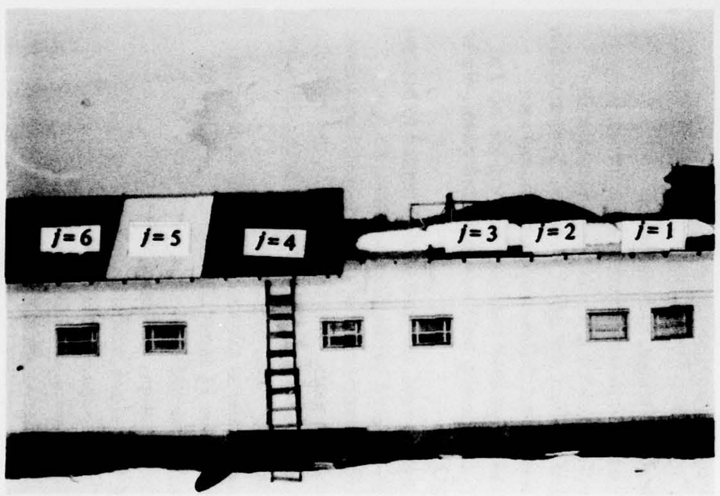
168

1555 17 Jan 73



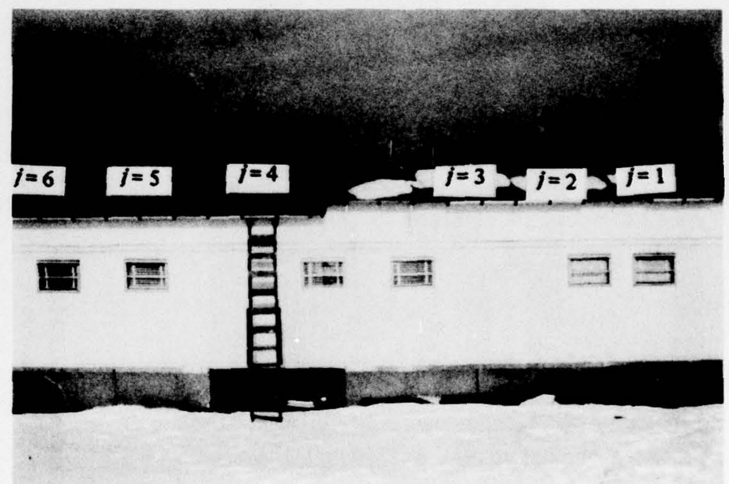
170

1350 18 Jan 73



172

1350 19 Jan 73



175

Figure 6c.

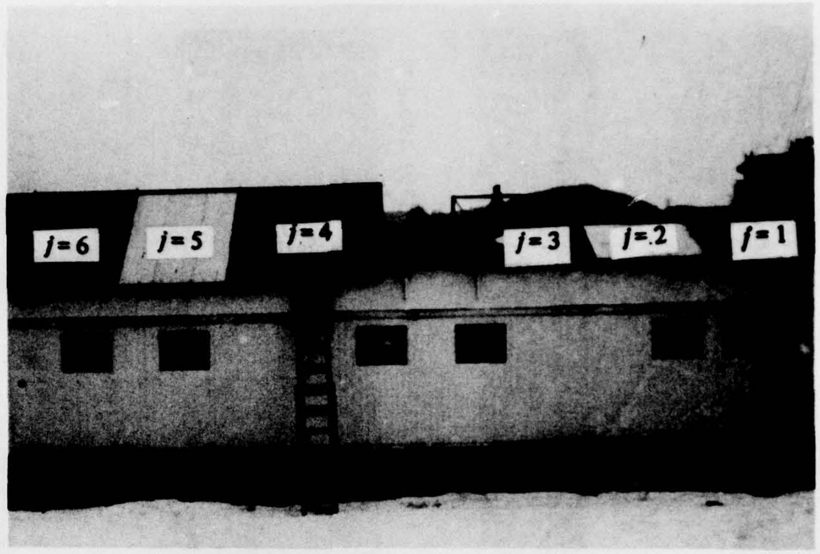


Figure 6d. 177

both the eave and the middle sections exhibited a marked rise in heat accumulation during daylight. This was probably due to the lack of snow cover of this roof for this test day.

In general, these results agree with the results obtained from the thermocouple data.

Snow depth, coverage, and meltwater

The snow depth was generally least for the high-slope roofs and, for a given slope, increased with τ', the size of the butt end of the shingles. The exception to this was the no. 2 (low-slope, aluminum) roof, which had the greatest tendency to form ice dams at the eave and thereby hold a deeper snow cover. Refer to Table XIII.

For a given roof, the eave section tended to become bare first followed by the ridge section. The no. 5 (high-slope, aluminum) roof often cleared days sooner than the other roofs. This can be seen in the sequence of photographs shown in Figure 6 and in the coverage data detailed in Table XIV.

The meltwater as a fraction of original snow cover averaged for the 18 snowfalls recorded in Table XV decreased in the order:

no. 5 (high-slope, aluminum) roof
no. 4 (high-slope, asphalt) roof
no. 2 (low-slope, aluminum) roof
no. 1 (low-slope, asphalt) roof
no. 3 (low-slope, cedar) roof
no. 6 (high-slope, cedar) roof.

In comparison, the total meltwater volume averaged for the same snowfalls decreased in the same order except that the no. 5 (high-slope, aluminum) and no. 6 (high-slope, cedar) roofs exchanged positions. While the no. 5 (high-slope, aluminum) roof produced the least meltwater volume per snowfall, a greater fraction of its snow cover ran off as meltwater following the snowfall's cessation. The no. 6 (high-slope, cedar) roof produced the most meltwater volume but the least fraction of its snow cover ran off as meltwater.

If the results above are compared with the results for the temperature ranking for the middle section, the data seem to say that the cooler the roof the more meltwater it produces. This apparent contradiction is erased when the effects of slope are considered. The meltwater produced by the high-slope roofs tends to run off more rapidly than that produced by the low-slope roofs, which freeze more of their meltwater into ice dams because of the slower rate of flow.

Degree of icing

Table XVI records the observed degree of icing, *I*. For the 12 observation times, the average value of *I* decreased in the order:

no. 2 (low-slope, aluminum) roof
no. 3 (low-slope, cedar) roof
no. 1 (low-slope, asphalt) roof
no. 5 (high-slope, aluminum) roof
no. 6 (high-slope, cedar) roof
no. 4 (high-slope, asphalt) roof.

This result implies that the higher the slope, the less likely the roof was to ice; and for a given slope, aluminum was the most likely and asphalt the least likely to ice.

Discussion of the icing problem

If the semi-quantitative indicator I could be expressed as a quantitative function of the relevant variables, the following assumptions might reasonably be stated:

$$1)\ I \propto (T_M - T_E) \quad \text{if} \quad T_M > T_E \tag{3}$$

$$2)\ I \propto 1/V \tag{4}$$

$$3)\ I \propto h \tag{5}$$

$$4)\ I \propto \gamma \tag{6}$$

$$5)\ I \propto 1/\alpha \tag{7}$$

$$6)\ I \propto \tau' \tag{8}$$

$$7)\ I \propto k' \tag{9}$$

$$8)\ I \propto A' \tag{10}$$

$$9)\ I \propto S'. \tag{11}$$

All of these assumptions are supported to some extent by the results discussed previously.

If it is assumed that each of the nine assumptions is a valid statement about icing, which of the nine effects is most important? The answer is clearly assumption (5). The slope of the roof dominates its icing behavior. It does this by controlling h, γ, and V. If all the snow leaves the roof as meltwater or fallen snow, none will be left to freeze into ice. The assumptions concerning the effects of k' A' S' **and** τ' are the next most important statements. τ' determines the ability of the roof to hold snow cover for a given slope; i.e., a stepped slope can hold snow more readily than a smooth one and the greater the size of the steps, the greater the ability to hold snow. k', A', and S' determine the thermal interaction of the roof covering with the snow cover, solar radiation, heat leaking through the attic floor, and heat trapped under the eaves. They determine the value of $T_M - T_E$ and the profile of the roof.

The nine assumptions above could therefore be summarized by

$$I \propto k'S'\tau'A'/\alpha \tag{12}$$

and

$$I \propto \frac{[T_M(k',S',A') - T_E(k',S',A')]\, h(1/\alpha,\tau')\gamma(1/\alpha,\tau')}{V(\alpha,k',S',A')} \tag{13}$$

where eq 12 indicates the dependence of icing on the roof characteristics directly and eq 13 depicts the manner in which the roof characteristics act to control the icing. Equations 12 and 13 do not represent quantitative results; they represent the simplest form that quantitative results could take. It is therefore clear that each of the roof characteristics acts in an interrelated manner to affect V, h, γ, and the temperature profile of the roof, the conditions that lead to the formation of ice. While the slope is the most important characteristic, the other roof characteristics may, if they assume extreme values, enhance or counter the effect of the slope. Furthermore, it is clear that, as the size and frequency of snowfalls increase, the roles of the thermal characteristics will become more important because, once any ice has formed, it acts as a barrier to the flow of falling snow and meltwater, thereby effectively reducing the ability of the slope to prevent icing. Thus, for flat or nearly flat roofs (such as the protected membrane roof) the importance of the insulation and thermal and optical properties of the surface covering cannot be over-emphasized. The need for increased insulation in protected membrane roofs has been emphasized elsewhere.[1] The results here indicate that the choice of surface covering must receive equal attention.

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